The Environment of
AMCHITKA ISLAND
ALASKA

TID-26712

The Environment of **AMCHITKA ISLAND, ALASKA**

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FOREWORD

The scientific information presented in this volume was acquired in studies initiated by the former U. S. Atomic Energy Commission (AEC) in 1966.

In January 1975 the Atomic Energy Commission as an agency was disbanded. Many of the activities, including the nation's nuclear weapons program, were transferred to the newly created Energy Research and Development Administration (ERDA). Publication of this book has been completed under the auspices of ERDA; however, reference to AEC is frequently made to preserve historical accuracy.

* * * * *

In 1966 a military requirement was established for the development of the Spartan antiballistic missile system. This development required the proof-test of the nuclear warhead before deployment. Because the yield of this warhead would be larger than any underground nuclear test previously conducted by the United States (approximately 5 megatons), locating an appropriate nuclear test site posed a unique problem to the nation's nuclear weapons test complex. The principal problem was to locate a test site within the United States having appropriate geology that would insure containment of radioactivity and that was at a sufficient distance from high-rise man-made structures so that the ground motion from the nuclear detonation would not cause unacceptable damage to such structures. It soon became apparent that no location meeting these requirements could be found within the conterminous forty-eight states, and so attention focused on Alaska. Two locations in Alaska were selected for reconnaissance as possible test sites. One of these was north of the Brooks Range close to the Arctic Ocean in northwestern Alaska. The other was the island of Amchitka in the western Aleutian Islands archipelago. (Amchitka had been used previously for a low-yield nuclear test conducted in 1965 by the Department of Defense with AEC assistance.)

Ultimately, after the consideration of many factors, Amchitka was selected for the supplemental high-yield nuclear test site. It was necessary to take into consideration that the island had been designated as part of the Aleutian Islands National Wildlife Refuge and was under the administration of the U. S. Fish and Wildlife Service of the Department of the Interior. However, when the refuge was established by Presidential Executive Order No. 1733, on Mar. 3, 1913, it contained the following proviso:

Establishment of this reservation shall not interfere with use of the islands for lighthouse, military or naval purposes. . . .

Thus the temporary use of Amchitka as a nuclear weapons test site to fulfill a military need was deemed to be consonant with the spirit of the Executive Order, and the Secretary of the Interior gave permission for AEC to occupy and use Amchitka for nuclear tests.

Because Amchitka is a part of the wildlife refuge and because it possesses environmental and biotic features quite different from locations where other nuclear tests had been conducted, it was considered necessary to carry out a

program of bioenvironmental studies in support of the nuclear test mission. Accordingly, the Division of Military Application at AEC Headquarters provided funds for the Nevada Operations Office to initiate and administer an Amchitka Bioenvironmental Program. There was an important precedent to such bioenvironmental investigations in Alaska in the ones that were performed as part of the AEC's project Chariot studies from 1959 to 1961. The lessons learned from Chariot were very valuable in designing and conducting the Amchitka studies.

The Amchitka Bioenvironmental Program commenced in 1967 and continued to the time when the test activities were concluded, the site restored, and AEC personnel evacuated from the island in 1973. A small series of follow-up studies have been conducted periodically since that time.

It has been the policy of the AEC (and now ERDA) to publish and make available to the scientific community and the public results of the agency's unclassified research. It is the purpose of this book to compile and condense the information developed in these studies and to make this information broadly available. Much of the information was published earlier in progress or special topical reports; however, these reports did not receive very wide dissemination and thus are not readily available to the average reader. It is hoped that this book will be more readily accessible and reach a wider audience.

Since the studies that yielded the information contained herein were conducted to meet the mission needs of the nuclear weapons test program, their scope is not truly comprehensive in an ecological sense, and the reader can readily discover that there are gaps. In spite of these gaps, we believe this compilation of information is a valuable contribution to environmental science. One of the values is the fact that the studies were carried out nearly simultaneously at a common location and thus relate to each other in a more meaningful way than studies occurring in different time periods. The Energy Research and Development Administration is pleased to publish this book with the hope it will be an enduring and valuable contribution to the scientific literature.

/s/ Edward B. Giller
Deputy Assistant Administrator
for National Security

PREFACE

To many a wartime soldier or sailor, the Aleutians were the land that God forgot. The Coast Pilot comments on the weather of the Aleutians, "No other area in the world is recognized as having worse weather in general than that which the Aleutian Islands experience." Yet primitive man lived there and made a good living for thousands of years before the white man came to disturb him. William S. Laughlin points out that it was quite possible for primitive Aleut men or women to live into their eighties; by contrast, Eskimos in the true Arctic were lucky to see past their forties.

We who spent intermittent periods of time for six years on Amchitka, however, came to think of the island as a beautiful place in a grand, bleak way. I (Merritt) first went to the island in February 1968. One of the high points of that visit was a journey along the crest of the island on the old jeep trail while the wind swept great sheets of fine snow up the U-shaped valleys from the Bering shore and out in long horizontal fingers over the Pacific. We came to joke about the nearly constant summer fog, wondering if the plane would be able to make it in. Even then there was usually one day a week clear enough that the neighboring island to the north would show the seven peaks for which it was named Semisopochnoi. We recall with pleasure the occasional clear, warm days in the fall when the crowberry and lichen were soft on the hills, spray twisted around the rocks at the edge of the intertidal bench, and sea otter played with their young in the water beyond.

We were there for a purpose, a purpose that was stirring dissent and argument down where we came from and in the great state of Alaska, of which Amchitka is an outlying part. If there must be armaments in this less-than-perfect world, we wanted to know, as well as circumstances allowed, what we were doing in the testing of them, what sort of place we were into, and how we could minimize the effects of our intrusion. Programs in seismology, geology, hydrology, and the various subject matters included in the word biology were carried out to ascertain better what was there, to predict the effects of the nuclear tests to come, to minimize undesirable effects to the extent feasible, and to document what actually did happen.

In the course of this very applied and pragmatic endeavor, a good deal of fundamental, and we hope new, information was gained about a hitherto little-studied part of the world; it is the purpose of this book to bring together in one place a comprehensive summary of these results in the field of the life sciences. Results in the physical sciences are published elsewhere. It is not our primary purpose here to tell what happened as a result of the nuclear tests, although that is not ignored, or to produce an apology for the weapons program. But we do admit pride in the wealth of information that we here offer to the critical eyes of our fellow scientists. We hope that the body of knowledge summarized here will add to the understanding of our world and perhaps even be the basis for further work in these islands in the future.

In 1966 the Department of Defense asked the U. S. Atomic Energy Commission to design a nuclear explosive with an energy output larger than could safely be tested underground at the existing Nevada Test Site, the

limitation there being ground motion and its effects on high-rise buildings in Las Vegas. After a considerable search, the AEC went to Amchitka. Amchitka had geology suitable for the proposed tests and for containment of the resulting radioactivity, it was remote enough to give reasonable assurance of safety, and it was U. S. territory. Safety is first and foremost a concern about people. The most effective way to protect people is to be far from them, and Amchitka is far from people, as far as any place that can be found in the fifty states. The AEC was not entirely unfamiliar with Amchitka; it had participated in a Department of Defense underground nuclear test there in 1965. But unfortunately the biological program on that test was minimal and gave only a slight basis for predicting the consequences of much larger shots. A more comprehensive ecological program was in order.

In 1966 the Battelle Memorial Institute's Columbus Laboratories was managing a program of ecological studies in Panama for the AEC and the Atlantic-Pacific Interoceanic Canal Commission associated with the feasibility and safety of digging a new canal with nuclear explosives. Battelle was asked to organize studies at Amchitka as well.

The broad objectives of the proposed studies, as spelled out in the contract between the AEC and Battelle, were to conduct appropriate field and laboratory studies to predict, evaluate, and document the effects on the bioenvironment of Amchitka Island that might result from the proposed nuclear tests and to recommend measures for minimizing these effects.

Thus in 1967, two years before enactment of the National Environmental Policy Act of 1969, the program whose fundamental results are reported in this book began. These broad objectives had to be brought down to the level of specific concerns, a program outlined, and competent investigators sought. The first list of specific concerns, agreed to with the Fish and Wildlife Service in June 1967, ordered them:

1. Effects on the sea otter population.
2. Transport of radionuclides to man via marine processes.
3. Transport of radionuclides to man via migratory birds.
4. Disturbance of terrestrial habitats.
5. Disturbance of freshwater habitats.

The list and priorities within it changed as time went on. For instance, physical effects were certain; they deserved and later got top priority. Radiological effects were considered improbable since a leak of radioactivity was improbable; so they took second place. Radiation background levels, however, had to be determined, and they are reported in this book. The original work statement and this list of specific concerns emphasize man and his interests over the rest of the biosphere. Effects on the sea otter population took the top place on the list because of the importance of this animal in the public mind, the species having once been endangered as a result of human predation. The emphasis on sea otters continued to the end of the program.

The very applied nature of the bioenvironmental program dictated details in the design of the program. The program was selective; emphasis

was put on the highest trophic levels and on those species of greatest public interest. This resulted in important omissions: The whole question of decay of organic matter and return of nutrients to the soil was left out, as was entomology. The Norway rat population was not a subject of formal study, although these recently introduced animals play a role in the terrestrial ecosystem. As editors we now regret this oversight and have tried in this book to bring together information about rats that was gathered late or incidental to other parts of the program.

The AEC-sponsored ecological studies were carried out under the close scrutiny of the U. S. Department of the Interior, and the results of the investigations were reported regularly. The Fish and Wildlife Service of that department assigned four men to it, two refuge-management biologists who rotated to keep one man on the island at all times and two research-oriented men who monitored and participated in the research being carried on. One of these represented the Bureau of Sport Fisheries and Wildlife and the other the Bureau of Commercial Fisheries (now the National Marine Fisheries Service in the Department of Commerce). Annual progress reports went to four libraries in Alaska as well as to a number of repositories in the lower forty-eight states. A special session on Amchitka studies was featured in the 1970 annual meeting of the American Institute of Biological Sciences in Bloomington, Ind., and the papers given there were later published in the June 15, 1971, issue of *BioScience*. (Results of the program in the physical sciences have been published in the December 1972 issue of the *Bulletin of the Seismological Society of America* and elsewhere.)

The idea of putting together a book on the Amchitka investigations had a precedent in the AEC's proposed Chariot project. That project was suspended, but not before several seasons of intensive ecological studies had been completed. The book reporting the results of that program is the classic "Environment of Cape Thompson, Alaska," edited by Norman J. Wilimovsky and John N. Wolfe. Many of us believed that Amchitka too should have its book. This dream remained in the background for six years while more pressing concerns were attended to. However, when Cannikin was past, the test people had left, and cleanup of the island had started, the dream was remembered. It has now been realized in this book.

As an introduction to the discussions that follow, it is appropriate to call attention to the special position Amchitka occupies in a larger setting and to the forces that have influenced it in an ecological sense. The key to understanding the structure and dynamics of Amchitka ecosystems is a recognition that this is a truly oceanic island, a minuscule bit of land remote from any continent, and relatively isolated even from neighboring islands by deep ocean passes. It is important also to note that Amchitka lies along the boundary between two major ocean-water masses that differ significantly in temperature, salinity, and biological properties.

The North Pacific Ocean washes the southwest shore of Amchitka, and the colder, more saline waters of the Bering Sea break against the northeast coast. Through Amchitka Pass and Oglala Pass, at either end of the island, Pacific Ocean and Bering Sea waters mingle and exchange or blend some of

their disparate properties. Together these two water masses provide, in large measure, the environmental determinants and the driving forces that influence the terrestrial, freshwater, and littoral ecosystems of the island. Except for its bedrock geologic structure, there is almost no feature of the island—climate, vegetation, or fauna—that does not reflect the overriding influence of the seas around it and its remoteness from continental land masses. Even the prehistoric and historic intrusions of man onto Amchitka were primarily aimed at exploiting resources that depended on the maritime situation of the island.

The much maligned climate of Amchitka is a product of interactions between passing storm systems, generated by global atmospheric circulation, and the adjacent water masses, which differ in surface temperature. Frequent, abrupt changes in weather occur with the passage of storm fronts along or across the Aleutian arc; yet daily and seasonal fluctuations in air temperature are relatively small owing to the moderating effect of the seas. Fog or low clouds blanket the island much of the time, with the result that insolation is low as compared with continental locations at similar latitudes. The typically maritime climate strongly influences the aspect and productivity of terrestrial vegetation, whereas the composition of the flora reflects the isolation of Amchitka from continental floras.

The influence of the oceans extends as well to almost every other feature of the Amchitka biosphere. Five of the six species of fish found in the freshwaters of the island spend a part of their life cycle at sea, reach maturity in the productive marine environment, and return to freshwater to spawn. Well over half the species of birds of Amchitka derive all or a part of their sustenance from marine littoral or pelagic sources. The native mammals are all creatures of the sea or of the interface between sea and land. Even the nonindigenous Norway rat, which elsewhere subsists mainly on the refuse heaps of man, is found here most frequently on the ocean beaches where food is plentiful. Most of the chapters in this book will show, in greater or lesser detail, the dependence of Amchitka biota on the productivity and tempering influence of the seas around it.

The authors whose papers are gathered here have, for the most part, been with the program since near its inception. In those few instances where there had been a change in investigators, the most recent participants were recruited. Their papers are gathered into major sections on the Land, the Sea, Marine Mammals, and Environmental Contaminants. Preceding those sections is a group of papers that set the stage. After the main sections comes a one-paper section devoted to summarizing the effects of the nuclear tests on the island. As to the overall meaning of what we have learned, we can only say that research is always inherently incomplete and that each reader will have to summarize for himself.

Some will say it is a pity that it takes a nasty cause like weapons tests to produce the kind of detailed study that a place like Amchitka deserves. We who have spent an important part of our lives there would rather be glad that a necessary evil can nevertheless produce information of lasting value to mankind.

*M. L. Merritt
R. G. Fuller*

ACKNOWLEDGMENTS

No project the size of the Amchitka Bioenvironmental Program could possibly have come off as well as it did without the diligent efforts of a great number of people. There are too many to name, and even as we try we will probably omit some just because we could not keep track of them all.

First and foremost, there were the scientists themselves. They are a grand group of people; we enjoyed working with them and regret that we can never all be together again. The very process of having to live together at the end of an extended supply line created an interdependence and an esprit de corps that served wonderfully in smoothing over the inevitable small frictions of human intercourse and the tension of deadlines. Many are among the authors of this book and kept at it even after the money ran out. Then there were our anonymous referees who read these papers in earlier versions. We thank them all.

The program was sponsored by the Atomic Energy Commission, Division of Military Application, headed in its later phases by General Edward Giller, who took a great deal of personal interest in it. Giller's deputies, first Charles Winter and then Frederick Tesche, and his assistant for environmental affairs, Gordon Facer, smoothed our Washington problems a great deal.

The Milrow test was under the technical direction of the Los Alamos Scientific Laboratory, and the Cannikin test was under that of the Lawrence Livermore Laboratory. Their large test staffs, under William E. Ogle and James Carothers, respectively, spent a lot of time they did not have to on our problems.

The Amchitka Bioenvironmental Program reported directly to the AEC's Nevada Operations Office (NVO). James E. Reeves, Manager of NVO until 1969, was a strong early supporter of safety studies, one of which was this program. His successor, Robert E. Miller, gave close personal attention to what was happening within the program and many times made decisions in favor of program projects in the stubborn faith that this work was important too, even at the risk of interfering somewhat with the weapons test itself. Then, of all the wonderful people to work with, we must mention Jerry Davis, Ernie Campbell, and Ray Brechbill of the NVO Effects Evaluation Office. Ernie especially has followed through in support of this book to the very end; his unfailing encouragement and wise counsel have been invaluable.

The NVO supported all the activities on Amchitka through contractors and subcontractors reporting to a series of Site Managers appointed from the NVO engineering staff. We note especially Holmes and Narver, Inc., the basic island support contractor, and Universal Services, Inc., the housekeeping contractor who kept a magnificent kitchen. The Amchitka Bioenvironmental Program itself was set up through the Battelle Columbus Laboratories (BCL), and, although NVO chose to make some direct contractual arrangements later, the BCL influence was important throughout (and a BCL retiree is one of the present editors). Dr. Richard Davidson initially supervised setting up the program; Dr. James Kirkwood (now with the Fish and Wildlife Service) was recruited as overall Project Scientist and Field Director. Also important were Roger Evans as contract officer and Ian Mercier who served in a wide

variety of fields, especially including field coordinator of biological programs.

The Department of the Interior scrutinized the program carefully from the beginning. Refuge biologists were assigned by the Fish and Wildlife Service, one to be on the island at all times: these were John Hakala, LeRoy Sowl, Baine Catron, Clay Hardy, and Vern Byrd. Carl Abegglen (now retired) and Ted Merrell (since transferred to the Department of Commerce with his agency, now the National Marine Fisheries Service) were research-oriented staff members assigned to the project. In many instances Interior representatives took an active part in the field work.

Among other organizations that we interacted with, we especially remember Reeve Aleutian Airways, which gave yeoman service in support of our activities. All program participants remember William "Scotty" Matthews, our principal helicopter pilot, who came to know the island like a book and was just as good at telling stories; this knowledge made him a very effective assistant to the biologists. Bob Rausch from the Arctic Health Research Center did the autopsies on dead sea otters, seals, birds, and fish after Cannikin. Karl Schneider, Alaska Department of Fish and Game, always skeptical and sometimes disagreeing with our methods and purposes, was yet very helpful in sea otter studies and as a devil's advocate.

Finally, we must put in a good word for our collaborators from the Energy Research and Development Administration, Technical Information Center, in Oak Ridge, Tenn., Marian Fox and Jean Smith, who took our scratched-up manuscripts and with patience, good will, and professional expertise put them into the shape you see here.

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Geographic Setting

M. L. Merritt

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Amchitka Island lies at latitude 51.5°N and longitude 179°E. It is one of the Rat Island Group of the Aleutian Islands, Alaska, which comprise the emergent part of a long submarine ridge connecting North America and Asia and separating the Bering Sea from the North Pacific Ocean (Fig. 1). Amchitka is almost the southernmost Aleutian Island, only nearby Amatignak being farther south. It is thus almost the southernmost point in Alaska.

Amchitka is 2160 km (1340 statute miles) west-southwest of Anchorage, Alaska, and 4000 km (2500 miles) west-northwest of Seattle, Wash. It is almost half the way from North America to Asia, being 1400 km (870 miles) east of Petropavlovsk, Kamchatka, U.S.S.R., and 1230 km (765 miles) west of the tip of the Alaskan mainland at False Pass.

Amchitka and all the Aleutian Islands except a few of the easternmost ones are in the Aleutian Islands National Wildlife Refuge. All the investigations reported in this volume except for a few (e.g., sea otter and oceanographic studies) were carried out on Amchitka or in the nearby sea.

MAPS

The U. S. Army Map Service has prepared good topographic maps of the island in 1 : 25,000 scale as follows: Rat Islands sheets 2123 IV NW, 2023 I NE, 2023 I NW, 2024 II SW, 2024 III SE, 2024 III NE, 2024 III NW, 1924 II NE, in series Q801 [also designated, in the same order: Rat Islands (A-2) NW, (A-3) NE, (A-3) NW, (B-3) SW, (B-4) SE, (B-4) NE, (B-4) NW, and (B-5) NE]. These maps were prepared from aerial photographs taken in September 1948 and field surveys of 1949 and have a contour interval of 50 ft. As part of the Atomic Energy Commission (AEC) program on Amchitka, new aerial photographs were taken in 1968. From these photographs forty-one 1 : 6,000 scale maps covering the island with a contour interval of 10 ft were prepared. These maps are no longer available.

The region is shown in one generally available U. S. Geological Survey topographic quadrangle

map, the 1 : 250,000 scale Rat Islands Sheet. This sheet is the result of a reconnaissance survey during the wartime years and is not satisfactory for more than the most general use. Another regional map generally available is the Sectional Aeronautical Chart of the Western Aleutian Islands issued by the National Oceanic and Atmospheric Administration National Ocean Survey in 1 : 500,000 scale.

The bathymetry of the surrounding seas is shown in the Environmental Science Services Administration (ESSA)/Coast and Geodetic Survey map sheet Kiska 1910N-1 of the 1 : 400,000 series "Bathymetry for the Aleutian Arc," reprinted from ESSA Monograph No. 3. This map sheet includes the whole of the Rat Islands from 175 to 180°E longitude. Inshore bathymetry is best shown in a set of four maps prepared by Doeringfeld, Amuedo, and Ivey of Denver, Colo. (now Amuedo and Ivey, Consulting Geologists). These maps are the East Cape, Makarius Bay, Chitka Cove, and Bird Cape sections, Amchitka. Copyright of these four maps remains with Amuedo and Ivey.

Two Coast and Geodetic Survey Navigational Charts cover Amchitka and vicinity. These are Chart No. 8864, Rat Islands (Semisopochnoi to Buldir Islands) at 1 : 300,000 scale; and Harbor Chart No. 9123, Constantine Harbor, Amchitka, at 1 : 10,000 scale.

Finally, the U. S. Geological Survey has prepared a new Amchitka Island Quadrangle at 1 : 100,000 scale for this volume. It has contour intervals on land of 100 ft and at sea of 25 ft to a depth of 300 ft and 100 ft below that. This map is based on the U. S. Army Map Service and the Amuedo and Ivey maps. A copy of this map is in the pocket at the back of this volume.

POPULATION

The region around Amchitka is sparsely populated. In the whole Aleutian Islands Census Division, which includes part of the Aleutian Peninsula, there were only 8057 people in 1970 (Bureau of the Census, 1971). All communities

Fig. 1—Amchitka's position between Asia and North America.

listed by that census are shown in Fig. 2. The nearest populated places to Amchitka were then and still are the Adak Naval Station [300 km (190 miles) to the east] with a 1970 population of 2249 and the Shemya Air Force Base [370 km (230 miles) to the west] with a population of 1131. Not reported by the census is a small U. S. Coast Guard contingent on Attu just west of Shemya. The nearest nonmilitary point of habitation is the village of Atka [450 km (270 miles) east] with a population of 88, all Aleuts except the schoolteacher and his wife. Almost equally distant [about 800 km (500 miles)] to the east and west are the Aleut village of Nikolski on Umnak Island, population 57, and Mednyi (Copper) Island in the Russian Komandorskie Islands, which Hrdlička (1945, p. 397) reported had a population of about 150 in 1938. Amchitka itself has not had a permanent resident population since 1849 (Dall, 1877), although it has been intermittently occupied several times since then, most noticeably by the military in World War II and for a short while thereafter, during the Long Shot test, and from 1967 to 1973 by the AEC (Chap. 6, this volume).

The Aleutians lie nearly on a great circle from Anchorage, Seattle, or San Francisco, Calif., to Japan; so daily flights and frequent ship traffic pass by within a few hundred miles. In addition, the seas to both sides of the Aleutians are heavily fished at some seasons of the year (Chap. 15, this volume). Japanese or Russian trawlers can occasionally be seen from the island.

TOPOGRAPHY AND APPEARANCE

Amchitka lies entirely within the Alaska–Aleutian physiographic province (Wahrhaftig, 1965) and, biologically speaking, is an archetype of a maritime tundra regime.*

Amchitka is 65 km (40 miles) long and 2 to 7 km (1 to 4 miles) wide and has an area of about 30,000 ha (74,000 acres). As with other Aleutian Islands, Amchitka has a rugged coastline with sea cliffs and grassy slopes up to 30 m (100 ft) high nearly completely surrounding the island (Fig. 3). Sand beaches on the island are so few that their rarity occasions mention of the fact in some place-names. Only a few of the beaches, such as the one at the head of Constantine Harbor and the one at the northwest end of the island between Aleut Point and Bird Cape, give reasonably easy access

inland. Much of the island is fringed by a wave-cut bench of rock as much as 100 m (330 ft) wide (Fig. 4). There is only one harbor on the island, Constantine Harbor on the Bering Sea side near the east end, and it is so exposed that, during storms from the northeast, ships must leave the dock. South Bight on the Pacific Ocean side and Chitka Cove on the Bering Sea side are sometimes used as shelters from storms (Coast Pilot, 1954).

The eastern third of the island is gently rolling country characterized by many shallow ponds with little or no drainage connections and streams half hidden by the seemingly ubiquitous cover of vegetation (Fig. 5). In the higher central portion of the island, this gives way to areas of more integrated drainage and greater wind erosion, with fewer lakes and with patches of bare bedrock rubble on ridges over 60 m (200 ft) high caused by diurnal freeze–thaw and high winds (Fig. 6). West of Chitka Point the island becomes quite mountainous, reaching a maximum elevation of 354 m (1160 ft) (Fig. 7). Here vegetation is quite sparse except in protected areas, such as stream valleys. Finally, the westernmost 5 km (3 miles) or so is a windswept rocky and barren plateau about 240 m (800 ft) high.

As a result of the military occupation in World War II and the more recent AEC occupation, there are numerous signs of the presence of man. About 2000 Pacific huts, which look like and are commonly called Quonset huts, remain from the military days. These are scattered seemingly at random in the area near Constantine Harbor, half buried by turf berms against the elements and many lying well away from the remaining dirt roads (Fig. 8, see also Chap. 6, Fig. 7, this volume). The military built a jeep trail that became known as Infantry Road along the crest of the island from South Bight on the east end to the beach near Bird Rock at the west end. The AEC improved this trail into an all-weather road easily driven by passenger sedan, although it must be plowed clear of snow at times during the winter.

The military built three airplane runways. The original one, Fox Runway at the head of Constantine Harbor, was trenched before they left and is unusable. Baker Runway, which is 10,000 ft long by 300 ft wide and which has numerous paved taxiways and hardstands, is the main runway. It has been resurfaced by the AEC. During the AEC program it was equipped with full Ground Controlled Approach (GCA) instrumentation for landing in poor weather; this has been removed, but the strip remains an excellent landing place if the weather permits a visual approach. The third

*A helicopter pilot on the program remarked how similar Amchitka looked to the Outer Hebrides of Scotland where he had spent his boyhood.

Fig. 2—Location and population of places in the Aleutian Islands Census Division with populations over 25.

Fig. 3—Coastline near Square Bay.

Fig. 4—Intertidal bench in Square Bay.

Fig. 5—Coastline between Banjo and Crown Reefer Points.

Fig. 6—Patches of rubble on ridges inland west of Sea Otter Point.

Fig. 7—Mountains near Topside Creek looking east.

Fig. 8—Huts left from the military occupation south of Constantine Harbor.

runway, Charlie Runway, has not been maintained and was used only once during AEC occupation.

The port facilities in Constantine Harbor were originally of wood but have been completely rebuilt of steel piling and timber decking. They should remain in good condition for a long time (Fig. 9).

During the AEC occupation a main camp to house 750 people was built on a hardstand off the southwest end of Baker Runway (Fig. 10). At the end of 1975, only three barracks and the kitchen—mess hall building remained of this. For a short time there was a small camp at Topside, halfway through the mountains, and for a number of years there was a 200-man camp at the northwest end of the island; both of these have been closed down, and all buildings have been removed.

Fig. 9—Port facilities in Constantine Harbor.

Fig. 10—Main AEC camp.

STUDY AREAS

The three underground nuclear explosions at Amchitka were Long Shot in 1965, Milrow in 1969, and Cannikin in 1971. Long Shot was sponsored by the military; its minimal biological program did not have a well-defined study area. Milrow and Cannikin were at the so-called B and C sites as shown in Fig. 11. Milrow was on the Pacific Ocean side of the island divide and Cannikin on the Bering Sea side. Both are in the eastern third of the island; Cannikin, at an elevation of 63 m (208 ft), was at the eastern edge of the region where bare rubble patches begin to appear.

The areas of most intensive study on Milrow and Cannikin were those within 5 km (3 miles) from the sites. The island is so long that more distant areas could be and were used as control areas not expected to be affected by the tests. Access to these areas was good where the roads existed. Access to offroad points was by foot, boat, helicopter, or Snow-Trac, a light-weight tracked vehicle.

TIME ZONES

Amchitka is nearly at the 180th meridian of longitude but keeps Bering Standard and Bering Daylight Times (165°W and 150°W meridian times). These times are related to Universal Time [Greenwich Mean Time (GMT)] as follows: BST = GMT - 11 hr; BDT = GMT - 10 hr; and local sun time = GMT - 12 hr 4 min, approximately.

PLACE-NAMES

Amchitka has been known by western man since the 1750s, but few of the early names survive. Bergsland (1959) has reported some of the native Aleut place-names for features on Amchitka as they were known in 1950 (Table 1). Certain of these appear to be of Russian or modern origin; for instance, the Russian word for harbor, gavan' (ГАВАНЬ), is used; and the name numbered 1023 in Table 1, which I have been unable to correlate with any known feature, appears to be anecdotal. The word Amchitka itself, however, is a genuine native name reported from early in Russian times (Orth, 1967).

Place-names used by project people were to a large extent new names, invented ad hoc for the many features that had to be kept track of and for which no previous names appeared to exist. Names given on the U. S. Army Map Service maps were used, but, in the process, few other names used earlier by the military or by the refuge manage-

Fig. 11 — Locations of major exploratory holes.

Table 1—Aleut Place-Names on Amchitka*

Aleut name	Description or translation	Modern name	Bergsland's listing number
<i>amcigtar</i>	Amchitka	Amchitka Island	1008
<i>amcigta-qakaya</i>	The east side of Amchitka		1009
<i>amcigtam qakayan tanriyis</i>	The islets at the east side of Amchitka	Sea Otter Rocks	1010
<i>tumgas uda</i>	Ivory bay	South Bight	1011
<i>sadali-magis</i>		Sea lion rocks off Ivakin Point	1012
<i>agu'ur</i>	A stay	Whale Cove	1013
<i>amcigtam ga'vana</i>	Amchitka harbor	Constantine Harbor	1014
<i>ga'vana-ya'ra</i>	The point at the harbor	Kirilof Point	1015
<i>kiji'lam uda</i>	Kirilof bay	Kirilof Bay	1016
<i>tanasulur</i>	The big inshore island	Bat Island	1017
<i>ga'vana-sitaca</i>	The other side of the harbor	Makarius Bay	1018
<i>tanasur</i>	The inshore island	Rocks off St. Makarius Point	1019
<i>tijinti-ya'ra</i>	Terenty's Point	Rifle Range Point	1020
<i>tanam ala</i>	The middle of the island	Duck Cove (?)	1021
<i>yam adugis</i>	The long reefs	Not identified	1022
<i>si'duj hasa'</i>	Cedor's skerry	Not identified	} 1023
<i>afana:sim hasa'</i>	Afanasy's skerry		
<i>ju'f hasa'</i>	Rolf's skerry		
<i>hanitgur</i>	A village and a stay	Site 49-RAT-66 in Cyril Cove	1024
<i>isuris ya'ra</i>	Hear seals point	Crown Reefer Point	1025
<i>anamgir</i>			1026
<i>ciranarsga'</i>	There is a creek	Falls Creek	1027
<i>cirsagtar</i>	Partly shallow	Limpet Creek	1028
<i>wala:g</i>	A group of sea lion rocks	Column Rocks	1029
<i>cimig</i>	The two tracks	Column Ridge	1030
<i>alag hatar</i>	Has wind from two directions	Chitka Cove	1031
<i>alag hata-tanasu'</i>	The inshore island at alag hatar		1032
<i>unanas latu'</i>	Cookers' lagoon	Chapel Cove	1033
<i>amcigtam nar'ir aqta'</i>	The western end of Amchitka		1034
<i>ta'gular</i>	Thirsty	Aleut Point	1035
<i>sa'tanas</i>	Bird's place or lying towards the front	Bird Rocks	1036

*Data taken from K. Bergsland, Aleut Dialects of Atka and Attu, *Trans. Amer. Phil. Soc.*, 49(3): 40-41 (1959). Phonological symbols used are explained by Bergsland on p. 8 of the journal, whence this table of "segmental phonemes":

Vowels	a			i		u
long	a [•]			i [•]		u [•]
Glides	—			y		w
aspirated	h			Y		F
Nasals	ŋ			n		m
aspirated	ŋ [•]			N		M
Liquids				j		l
aspirated						L
Spirants	r	g	z			v
aspirated	R	G	s			f
Stops and affricates	q	k	c	T	t	p

ment survived. Table 2 lists those place-names for features other than lakes or streams commonly used during the program and hence elsewhere in this volume. The Geological Survey map in the pocket at the back of this volume shows the location of most of these. Table 2 also indicates which of these place-names predate the AEC occupation and which ones have been submitted to and have received acceptance by the U. S. Board on Geographic Names and hence are fully acceptable and official. Not all names used were submitted, and not all that were submitted were

accepted. Nevertheless, these unofficial names served an essential purpose.

Table 3 gives place-names of lakes and streams. Almost all of these are unofficial names. The two biological projects most concerned with lakes and streams, the project on limnology of the Battelle Columbus Laboratories and the project on freshwater ecology of the Utah State University (reported in Chaps. 13 and 14, respectively, this volume), each created an accounting system to designate lakes and streams. Their designations are cross-referenced in Table 3.

Table 2—Place-Names on Amchitka Other Than Lakes and Streams

Name	Status	First use*	Bergsland's listing	Comment
Aleut Point	†	1935 USN	1035	
Amchitka	†	<1741 Aleut	1008	
Andesite Point	‡			
Baker Runway	†	1955 AMS		
Banjo Point	‡	1960 USGS		
Bat Island	‡		1017	Fault Block Island
Bird Cape	†	1836 IRN		Мыс Птичий
Bird Rock	†	1935 USN	1036	
Buoy Point	‡			
Burr House Cove	†	1957 AMS		
Chapel Cove	†	1957 AMS	1033	
Chapel Cove Island		RM		
Charlie Runway	†	1955 AMS		
Chitka Cove	†	1951 USGS	1031	From "Amchitka"
Chitka Point	†	1935 USN		
Chitka Ridge	‡			
Clevenger Lake	†	1955 AMS		
Clevenger Road	†	1957 AMS		
Column Ridge	‡		1030	
Column Rocks	‡		1029	Trident Rocks
Constantine Harbor	†	1849 IRN	1014	Гавань Константина
Constantine Point	†	1944 ACP		
C P Bluff	‡			
Crown Reefer Point	‡		1025	
Cyril Cove	†,‡	1944 ACP		Variant: Kirilof Cove
Duck Cove			1021 (?)	
East Cape	†	1855 USN		
Engineer Road	†	1955 AMS		
Fault Block Island		RM		Bat Island
Fox Cove		RM		Signal Cove
Fox Runway	†	1955 AMS		
Fumarole Cove	‡			
Galion Pit				At coordinates 536975
Grampus Point	‡			
Infantry Road	†	1957 AMS		
Ivakin Point	†	1852 IRN		Мыс Ивакин
Jones Lake	†	1955 AMS		
Kirilof Bay	†	1836 IRN	1016	
Kirilof Islets				Islands at harbor mouth
Kirilof Point	†	1935 USN	1015	
Landslide Cove	‡			
Loran Island		RM		St. Makarius Islands
Low Bluff	†	1855 USN		
Makarius Bay	†	1951 USGS	1018	St. Makarius Bay
Mex Island	‡			
Midden Cove	‡			
Midden Point	‡			
North Bight	‡			
Omega Point	†	1955 AMS		
Peregrine Point	‡			
Petrel Point	‡			
Pillow Point	‡			
Pluton Cove	‡			
Rifle Range Point	‡		1020	
Rifle Range Road				Clevenger Road

(Table continues on page 10.)

Table 2—(Continued)

Name	Status	First use*	Bergsland's listing	Comment
Rim Point	‡			
St. Makarius Bay				Makarius Bay
St. Makarius Islands			1019	Loran Island, off St. Makarius Point
St. Makarius Point	†	1935 USN		
Sand Beach Cove	‡			
Sandy Cove	‡			
Sea Otter Point	‡			
Sea Otter Rock	†	1955 AMS	1010	
Signal Cove	‡			Fox Cove
South Bight	†	1946 ACP	1011	
Square Bay	‡			Variant: Cyril Cove
Square Bluff	†	1855 USN		
Stone Beach Cove	‡			
Topside Camp	†	1957 AMS		
Trident Rocks		RM		Column Rocks
Vista Island		RM		
WE Site		RM		
Whale Cove	‡		1013	
White House Cove	†	1957 AMS		
Windy Island	‡	1960 USGS		

*USN, place-names given by a navy expedition; AMS, place-names that first appear on an Army Map Service map; IRN, place-names given by the Imperial Russian Navy; RM, place-names appearing first in Refuge Manager's reports; and ACP, place-names appearing first in the Alaskan Coast Pilot. (Data taken from D. J. Orth, *Dictionary of Alaska Place Names*, U. S. Geological Survey, Professional Paper 567, 1967.)

†Place-names that appear on Army Map Service maps.

‡Place-names newly accepted by the Board on Geographic Names.

Table 3—Amchitka Place-Names of Lakes and Streams

	USU*	BCL†	Coordinates‡	
Big Lake	AG		667961	
Bridge Creek	AA	§	518018	
Burr House Creek			206218	
Cannikin Lake			467040	
Chapel Cove Creek			281200	
Clam Lake	BI	22	522985	
Clear Pond		36	494034	
Clevenger Creek	AF		512968	
Clevenger Lake	AC	¶	555946	
Clevenger Lake Outlet	AB		552947	
Clover Lake			629942	
Deep Lake			417069	
Duck Cove Creek			504979	
Duck Pond		10	515962	
Emerald Lake	AU	51§	430066	
Falls Creek		§	400073	
Fault Lake	AN	58a	392111	
Fumarole Creek			316137	
Fox Runway Creek			586957	
GE Lake			625972	
Grauman Lake				Quonset Lake
Heart Lake	AK		516981	
Island Pond				Pumphouse Lake
Jones Lake	DA	5¶	576965	
Limpet Creek		§	367099	

Table 3—(Continued)

	USU*	BCL†	Coordinates‡	
Little Lake			527987	
Long Lake		§	565932	
Long Shot Lake		29	512002	
Long Shot Pond		30	514006	
Lower Twin Lake	BU	24	518984	
Mason Lake			561955	
Midden Creek			234208	
Mud Pond		35	493034	
Pratfall Lake	AP		529979	
Pumphouse Lake	AJ	1	585932	Island Pond
Quonset Lake	AQ	28§	519999	
Range Pond		7	515965	
Rifle Pond		9	516963	
Rifle Range Creek				Clevenger Creek
Rifle Range Ponds		7-12		Range, Rifle, and nearby ponds
Roller Coaster Creek	AD		636972	
Round Lake	DD	31b	521016	
Sewer Pond				Long Lake
Signal Cove Creek (N&S)			224165, } 222168 }	Two streams
Silver Salmon Creek (outlet)			546993	
Silver Salmon Lake	AL	19b§	541990	Pistol Lake (military name)
Sixty Four Lake			641963	
Strange Pond		33	493030	
Teal Creek		§	427037	
Tent Lake		15	522976	
Tern Lake			515026	
Tin Lake			571972	
Topside Creek			273159	
Twin Lakes				Upper and Lower Twin Lakes
Ultra Creek		§	465001	
Upper Twin Lake	BL	23	518986	
Weed Lake	BT	26	527994	
White Alice Creek		§	477050	
White House Cove Creek			303148	
Wild Lake				Quonset Lake

*Notation for this lake or stream used by freshwater ecologists from Utah State University.

†Notation for this lake used by limnologists from Battelle Columbus Laboratories.

‡Coordinates are based on the 1000 meter Universal Transverse Mercator Grid, zone 60. First three digits are the east coordinate and the second three the north coordinate to the nearest 100 meters. Thus 303148 means E630300, N 5714800.

§ Name newly accepted by the Board on Geographic Names.

¶ Name appearing on Army Map Service maps

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Geologic History

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Amchitka Island is one of the most southerly islands in the Aleutian Island arc. In general terms its geologic history is probably representative of most of the Aleutian Islands. Three distinct volcanic episodes have been recognized and dated by fossil evidence and by radiometric dating. The oldest of these is early Tertiary, probably Eocene, and is represented by altered basic to intermediate submarine lavas and volcanic debris. Next, coarse turbidites and other sediments of basaltic debris shed from nearby volcanoes were deposited on the sea floor during late Eocene or early Oligocene time. After a period of uplift, tilting, faulting, erosion, and invasion by small dioritic plutons in mid-Tertiary time, a subaerial volcanic complex of andesitic composition was constructed during the Miocene. At that time the island probably stood higher above sea level than

at present and trees were common. This volcanic complex is probably genetically related to one of the Miocene plutons. During Pliocene time minor shallow basaltic and hornblende andesitic intrusions occurred. In early Pleistocene time the island was still above sea level, the climate was somewhat warmer than now, and trees were present. During glacial and interglacial episodes, sea level fluctuated. During glacial periods terraces were carved as much as 91 m below sea level, and deposits of two episodes of glaciation are preserved. During interglacial times flights of marine terraces were cut above present sea level, and marine deposits on the island are correlated with two of them. Tensional faulting continued into Wisconsinan time; however, the island appears to have been tectonically stable during the past 2000 to 4000 years.

Multidisciplinary studies by the U. S. Geological Survey (USGS) conducted on and near Amchitka Island from 1964 to 1972 have contributed to a better understanding of the geologic, hydrologic, and tectonic environment of the island. These investigations are the only comprehensive earth-science studies made in the Aleutians and constitute the first intensive geologic study of the area since reconnaissance mapping by the USGS during the 1940s and 1950s (e.g., Powers, Coats, and Nelson, 1960). A geologic map of Amchitka Island is being compiled at a scale of 1 : 48,000.

This chapter summarizes the geologic history of Amchitka Island as determined from these studies and provides a brief description of the Aleutian Island arc.

GEOLOGIC SETTING

The Aleutian Arc

Amchitka Island lies in the western part of the Aleutian Island arc—one of the most striking physiographic features on the face of the earth. The arc consists of a curving submarine trench as deep as 7600 m, which extends 3200 km from the Gulf of Alaska across the north Pacific to Kamchatka, and a parallel ridge rising to the north, 3660 m above the Pacific Ocean floor. The eastern third of the ridge consists of the mountainous Alaska Peninsula. The western two-thirds of the ridge is an almost completely submerged mountain

range; the Aleutian Islands are the exposed peaks of this range. The Aleutian arc is one of many island arc systems that border the Pacific Ocean basin.

Formation of the Aleutian trench began during the Tertiary Period. The central and western parts of the trench are believed to have developed in the earlier half of the Tertiary (Hamilton, 1967), while the eastern end may not have been formed until Pliocene time (von Huene and Shor, 1969).

Unpublished marine geophysical data supplied by the Lamont-Doherty Geological Observatory suggest that the arcuate Bowers Ridge lying north of Amchitka Island may be part of an older inactive structural arc. Accordingly, Amchitka lies near the intersection of the Aleutian Ridge and the Bowers Ridge arcs (Anderson, 1971) (Fig. 1).

The Aleutian Ridge can be divided into a series of physiographically similar blocks (Fig. 1) separated by transverse canyons of probable structural origin (Anderson, 1971). Each block has a similar cross section: north and south slopes with a wide flattened crest topped by peaks, some of which rise above the ocean surface as islands. The south slope in many, but not all, places flattens to a broad terrace that commonly has closed depressions on it. Each of these physiographic blocks appears to be a seismic entity in that aftershocks of any major earthquake that may occur in a specific block are generally confined to that block and may continue for as much as a year after the quake (Jordan, Lander, and Black, 1965; Engdahl, 1971).

Fig. 1—Index map of central Aleutian arc showing major physiographic blocks and trace of east margin of uplift for the Bowers arc (heavy dashed line). Bathymetric contour interval, 100 m [From R. E. Anderson, USAEC Report USGS-474-75 (Rev. 1), U. S. Geological Survey, 1971.]

Amchitka lies on the Rat block, which is separated on the west from the Buldir block by the transverse Murray Canyon just west of Kiska Island and on the east from the Delarof block by a complex of submarine canyons in Amchitka Pass (Anderson, 1971, Plates 1A and 1B).

One of the most prominent features of the arc is the alignment of active and quiescent volcanoes along the northern edge of the ridge crest. Thirty-six of the seventy-six volcanoes have been active since 1760 (Coats, 1950); Kiska volcano extruded a small lava flow at sea level on its northern flank in 1965 or 1966.

The Aleutian arc lies along a zone of convergence between the Pacific Ocean floor and the Bering Sea floor. The leading edge of the Pacific plate is forced downward beneath the Bering Sea plate at the Aleutian trench, from which a well-defined zone of seismic activity at the plate juncture dips northward beneath the ridge. Engdahl (1971, Fig. 2) showed that hypocenters of earthquakes of magnitude 3.0 or greater near Amchitka Island, which were recorded during a 3-year period from 1969 through 1971, delineate a well-defined zone that plunges northward beneath the ridge from a depth of about 20 to 30 km beneath the Aleutian slope to a depth of about

250 km beneath the northern edge of the ridge—a horizontal distance of about 170 km.

During the 386-day period from Jan. 11, 1971, to Jan. 30, 1972, earthquakes having epicenters within a 60-km radius of the Cannikin underground nuclear explosion were plotted by Willis et al. (1972). During that period, 1559 events with body-wave magnitudes that ranged from 0.0 to 4.5+ were detected in this area. Of these, 1265 were shallow events (0 to 70 km deep) and 294 were intermediate events (>70 km deep). The readily apparent clustering of shallow events in the southern half and of intermediate events in the northern half of the circle supports the concept of a northward-dipping subduction zone. A similar pattern of seismic activity before and after the Cannikin event "suggests that the detonation of Cannikin did not alter the nature of the underthrusting process beneath Amchitka Island" (Willis et al., 1972, p. 55).

Despite the abundant evidence that the arc is located along a zone of convergence, most of the tectonic features visible on the islands or inferred from sea-bottom topography are of probable tensional origin. Abundant dikes, normal faults, grabens, and other submarine depressions, as well as the narrow zone of active volcanism, all suggest

Fig. 2—Geologic sketch map and cross section of Amchitka Island.

tensional stress. According to Anderson (1971, p. 1), these tensional features must reflect "... igneous-related tectonism including distension of the surficial skin over rising and spreading epizonal plutons, volcano-tectonic subsidence, and rifting..." Most of the faults crossing Amchitka trend east-northeast and probably first moved in late Oligocene or Miocene time before eruption of the Miocene Chitka Point lavas. Movement has continued on some faults into late Pleistocene time; however, there has been no significant fault movement on Amchitka in Holocene time.

Geologic mapping in the Aleutians indicates that the oldest rocks lie on the southern part of the ridge and the youngest occur in a narrow zone of active volcanoes along the northern edge. Melting and mixing of hyperfusible materials along the subduction zone beneath the arc provided the volcanic material that forms the ridge (Coats, 1962; Anderson, 1971). The north-to-south progression from younger to older rocks along the ridge suggests that the ridge may be migrating

slowly southward from a relatively fixed source of volcanism and is being rolled under itself along the zone of subduction (Anderson, 1971, p. 17). Recent geologic mapping on Amchitka (Fig. 2) has supplemented and modified the original study by Powers, Coats, and Nelson (1960). The new work included geologic mapping, isotopic dating, deep drilling, geophysical surveys, and hydrologic investigations.

This current work (Carr, Quinlivan, and Gard, 1970; Carr et al., 1971) has defined and dated rocks of three general episodes of volcanism: the Amchitka Formation, consisting of breccias of principally intermediate composition, monolithologic glassy breccias and pillow lavas, and local tuffaceous beds mostly of submarine origin, which is overlain by the Banjo Point Formation, consisting of breccias and minor pillow lavas that are mostly of basaltic composition, which, in turn, is overlain nonconformably by the Chitka Point Formation, consisting of subaerial lava flows, flow breccias, pyroclastic rocks, and minor tuffaceous

sediments and conglomerates, all of andesitic composition.

Faulting began in mid-Tertiary time and continued intermittently along certain faults into late Pleistocene time. Most faults exposed or interpreted on Amchitka strike generally northeastward, dip steeply northwest, and tend to repeat the stratigraphic section. Although they are normal faults, slickenside directions indicate that there has been some component of horizontal movement along many of the faults.

Physiography of Amchitka Island

Amchitka Island, in the west central part of the Aleutian arc, lies just west of the 180° meridian and just north of 51°N latitude. With the exception of Amatignak Island, about 100 km to the east, it is the most southerly of the Aleutian Islands.

Amchitka is about 65 km long and 5 to 8 km wide. It is roughly boot shaped and probably owes its shape, in part, to faulting. Except for the southeastern foot, it trends northwest, paralleling the trend of the Aleutian Ridge in the Rat block. The island is paralleled on the north by the steep slope of the Rat Islands escarpment and on the south by the Aleutian Slope, which descends to the trench. The Rat Islands escarpment descends steeply from a submerged Pleistocene terrace at -91 to -100 m to a maximum depth of -1500 m about 5 km northeast of the island. The escarpment bounds the south side of an area of graben-like closed basins on the sea bottom north of Amchitka.

The southeastern foot end of the island parallels and is delineated by east-northeast-trending normal faults that form grabens at Constantine Harbor and at South Bight.

The island can be divided into various landforms: a mountain segment, a high plateau, the Chitka Point segment, lower plateaus, and an intertidal bench (Powers, Coats, and Nelson, 1960).

The mountain segment, an erosional remnant of the Chitka Point volcano, lies between Chitka Point and Windy Island. It is composed of a sinuous ridge that rises as high as 366 m above sea level and roughly parallels the island axis. Extending north and south from this ridge are several steep U-shaped valleys separated by prominent ridges. Some of these ridges represent reversal of topography; they are formed of valley-filling lava flows that resisted erosion better than the underlying pyroclastic rocks of the Chitka Point Formation. To the southeast an outlier of the mountain segment, 300 m high, is separated from the main

part by a low saddle, Fumarole Valley, little more than 100 m above sea level. Intense hydrothermal activity in this area altered the rocks, allowing them to be easily eroded. Solifluction is exceptionally active there today.

Northwest of the mountain segment, a high partly dissected plateau, ranging in altitude from 214 to 275 m, extends to Square Bluff. Except for this bluff, which is underlain by andesitic lava flows, the surface of the plateau is composed of deeply weathered hydrothermally altered pyroclastic rocks. Scattered well-rounded cobbles on Square Bluff (Powers, Coats, and Nelson, 1960, p. 525) are probably either remnants of conglomerate of the Chitka Point Formation or, more likely, remnants of outwash from glaciers covering the plateau. Andesite erratics as large as 1.5 m in diameter scattered on the plateau surface indicate that ice moved northwestward from the mountain segment.

There is no reason to believe that the high plateau was formed by marine planation. Except for the rounded cobbles on Square Bluff, evidence is lacking which would suggest that relative sea level during either the Pliocene or the Pleistocene Epochs was ever 214 to 275 m higher than at present. Indeed, a subaerial basalt flow at Cyril Cove, presumed to be of Pliocene age, suggests that relative Pliocene sea level was at or below present sea level. Altiplanation offers a simpler explanation for the origin of the surface in attributing it to solifluction and related mass movement, which tend to produce flat surfaces at high elevations and latitudes.

A smoothly rounded surface south of Chitka Point lies at the same altitude, 152 to 214 m, as Chitka Point Bluff and a small flattish area north of Windy Island (Fig. 3). The origin of this surface is probably also altiplanation. Weakly cemented iron-stained unfossiliferous gravel and sand, which crop out on the surface south of Chitka Point, I believe to be part of the Chitka Point Formation rather than a littoral-zone deposit as suggested by Powers, Coats, and Nelson (1960, p. 541). The mountain segment stands above the high plateau and Chitka Point segments because, in the mountain segment, the Chitka Point Formation is composed mainly of lava flows containing only subordinate pyroclastic rocks, whereas the areas that have been beveled by altiplanation are mainly pyroclastic rocks with subordinate lava flows.

The lower plateaus, especially prominent on the eastern half of the island (Figs. 3 and 4), are a flight of Pleistocene interglacial terraces discussed later in this chapter. Several landslides interrupt these interglacial marine terraces along the Bering coast. The largest of these lies just east of Chitka

Fig. 3—Map showing surfaces of planation, Amchitka Island. Altitudes determined at bases of abandoned sea cliffs except for surfaces between 152 and 214 m. Altitudes from Holmes and Narver, Inc., topographic map, 1 : 6000.

Fig. 4—Map showing distribution of marine terraces, eastern end of Amchitka Island. Altitudes from Holmes and Narver, Inc., topographic map, 1 : 6000, contour interval, 10 ft.

Fig. 5—Landslide near Chitka Point on Bering coast. The slide, about 1 km² in area, is in conglomerate, tuffs, and breccias of the Chitka Point Formation. Note disruption of interglacial marine terrace on the left side of the picture.

Point and is about 1 km² in area (Fig. 5). Its unmodified appearance suggests that it may be quite young. All have developed in poorly consolidated conglomerates and laharic breccias of the Chitka Point Formation and could have been lubricated by sea-level fluctuations during the Pleistocene or merely by seismic shaking of saturated rocks.

A terrace is currently being developed at about mean sea level around most of the island perimeter. This intertidal bench is well developed on fine-grained sedimentary rocks but poorly developed on coarse-grained sedimentary rocks and igneous rocks. Development of the intertidal bench on moderately coarse-grained turbidites* of the Banjo Point Formation is shown in Figs. 6, 7, and 8. The bench is inferred to be the result of frost action on

the sea cliffs (Powers, Coats, and Nelson, 1960) and of abrasion by stones on the ramp between the actively retreating cliff and the bench rather than of direct wave action. The frost-riven rubble is removed by storm waves. Streams cascading over the sea cliff locally have prevented freezing and delayed the cliff retreat (Fig. 9).

*A turbidite is a rock or sediment layer deposited from a gravity-influenced bottom-flowing current laden with suspended sediment, which moves swiftly down a sub-aqueous slope and spreads horizontally on the ocean floor. At Amchitka these turbid currents were probably initiated by earthquake-induced sliding. The resulting deposit is characterized by graded bedding; i.e., beds which are coarse-grained at the base, grading upward to fine-grained at the top.

Fig. 6—Discontinuous sandstone blocks in turbidite bed of the Banjo Point Formation. Note the upward decrease in grain size of turbidite. Kelp-covered intertidal bench is shown in foreground.

Fig. 7—Mex Island, an erosional remnant of resistant Miocene Chitka Point lava that filled a valley cut in breccia of Eocene or Oligocene Banjo Point Formation. Note fanned columns lying normal to the steep valley wall at center of island. The intertidal bench at low tide shows in foreground.

Fig. 8—Intertidal bench cut on breccia of Banjo Point Formation exposed at low tide. Firmly cemented erosion-resistant boulders project above bench surface. The berm at outer edge of bench is probably preserved from freeze and thaw mechanical weathering by constant wave splash. Note the water-filled crocod joints.

Fig. 9—Sea-cliff retreat caused by freeze and thaw. Bedrock cone is protected from freezing by a stream cascading over its surface. Bedrock is breccia of Banjo Point Formation. Note low-angle joint that extends from cliff at right across bedrock cone. Near high tide covers the intertidal bench.

Fig. 10—Pillow lava in upper part of Amchitka Formation 1100 m west of Constantine Harbor. Devitrification of glassy rinds allows differential weathering. The hammer in the center of the photograph is 30 cm long.

GEOLOGIC HISTORY

Eocene and Oligocene Epochs

The geologic history of the Aleutian Ridge is, in a general way, reflected by the history of Amchitka Island. The rocks of Amchitka (Fig. 2) record a long history of Tertiary volcanic activity. The oldest rocks on Amchitka Island, the Amchitka Formation of early Tertiary age (Carr, Quinlivan, and Gard, 1970), provide a local record of deposition and alteration of more than 2300 m of submarine pillow lavas, breccias, and turbidites of basic to intermediate composition. Toward the end of deposition of the Amchitka Formation, a thick pile of monolithologic glassy breccias and at least two pillow lavas (Fig. 10) were extruded on the sea bottom.

Following this episode of local volcanic activity, after only a short interval of time, the Banjo Point Formation was laid down during late Eocene or early Oligocene time. Although locally there are submarine lavas at the base of the formation, the Banjo Point Formation consists almost entirely of fossiliferous marine volcanoclastic rocks. These rocks are mainly turbidites that range from coarse breccias to mudstones composed of basaltic rock fragments (Fig. 11).

There is considerable evidence to indicate that the turbidites were derived from material shed

Fig. 11—Coarse-grained turbidite bed in Banjo Point Formation. The bed grades from angular boulder-sized clasts at base to angular pebbles and sand at top.

Fig. 12—Rounded boulders of previously deposited breccia in a coarse-grained turbidite bed of the Banjo Point Formation.

from the sides of nearby ancient subaerial volcanoes. This debris slid down the submarine flanks of the volcanoes as turbidity currents and was deposited on the sea floor. Because of their density these submarine slides had the ability to transport huge blocks of eroded material; yet, curiously, they occasionally were remarkably gentle in their handling of these large blocks. Rounded blocks of displaced breccia (Fig. 12) as large as 5 m in diameter and sheets of sandstone 1 m thick and 100 m long have been observed. Many of the discontinuous sandstone sheets conform to the attitude of the enclosing turbidite beds but pinch out abruptly or degenerate laterally into discontinuous blocks of sandstone (Fig. 6).

Foraminiferal and molluscan assemblages found in the finer grained turbidites indicate a late Eocene or Oligocene age for the Banjo Point Formation (Carr, Quinlivan, and Gard, 1970). Because of a major erosional unconformity at the top of the formation, no complete section of the Banjo Point Formation is exposed. Although it

crops out over much of the eastern half of the island, the section has been repeated by normal faulting. The maximum known thickness of Banjo Point Formation is 967 m, penetrated in an exploratory drill hole at site B (Fig. 2).

Miocene Epoch

In mid-Tertiary time, uplift, erosion, and initiation of normal faulting along mainly northeast-trending faults occurred on Amchitka. Uplift appears to have occurred throughout the central and western Aleutian Ridge (Gates, Fraser, and Snyder, 1954) and was accompanied by intrusion of widespread epizonal plutons. A concordance of potassium-argon isotopic dates of plutonic rocks from Shemya to Unalaska (Scholl, 1972) tends to confirm a widespread period of plutonism and, hence, uplift during middle and late Miocene time.

On Amchitka this intrusive episode is represented by two separate small plutons, one cropping

Fig. 13—Typical outcrop of East Cape pluton showing wide-spaced blocky jointing.

out at East Cape and the other at White House Cove. The East Cape pluton (Fig. 13), which varies in composition from gabbro to biotite granite, invaded rocks of the Amchitka Formation. Contact metamorphism has locally changed wall rock and roof pendants to hornfels and amphibolite gneiss. A potassium–argon date of 15.8 ± 0.7 million years was obtained from a biotite-bearing phase of the pluton (Carr, Quinlivan, and Gard, 1970).

The White House Cove pluton (Fig. 14), a diorite porphyry that is exposed in only a few places, probably underlies much of the western third of the island and is believed to be genetically related to the Chitka Point Formation. The undated White House Cove pluton has the same negative remnant magnetization as the Chitka Point Formation but is different from the weakly positive magnetization of the East Cape pluton.

The mountainous western third of Amchitka Island consists of remnants of a subaerial volcano. These rocks, the Chitka Point Formation, clearly indicate that in late Miocene time, after the earlier Tertiary marine rocks of the Banjo Point Formation had been uplifted, faulted, and eroded, strato-volcanoes were built on the remnants of the ridge. The volcanic complex, which probably was a linear

series of cones, is believed to have stretched from the middle of Amchitka northwestward to the eastern part of Rat Island (Carr et al., 1971) and may have been 17 km wide.

Cauldron subsidence associated with the Chitka Point volcanic rocks is suggested by a prominent arcuate negative magnetic anomaly, the White House Cove anomaly (Bath et al., 1972, p. 22). Subsidence is further suggested by drill-hole information at sites E and F (Fig. 2), by anomalous seismic velocities within the postulated cauldron (Engdahl, 1973), and by an arcuate fracture pattern (not shown in Fig. 2) north of Windy Island. Three potassium–argon dates of 12.4 ± 1.1 , 13.2 ± 1.2 , and 14.1 ± 1.1 million years on Chitka Point lava flows confirm a middle to late Miocene age for the Chitka Point Formation, as indicated by a fossil-pollen assemblage (Carr, Quinlivan, and Gard, 1970), and thus the same age for the White House Cove pluton.

At that time sea level was relatively lower—or the ridge was relatively higher—than it is today. Stumps of trees in growth position found in a laharic breccia 23 m below sea level (Barr, Ellis, and Helle, 1973; Humphrey and Branstetter, 1973) provide evidence that relative sea level may have

Fig. 14—Intrusive contact of light-colored White House Cove pluton with darker pyroclastics of the Chitka Point Formation. A geologist is standing on the fine-grained chill border. Note porphyritic texture of diorite in pluton on left.

been at least 23 m lower. The site of these stumps, however, lies near the offshore extension of the Teal Creek fault, which has dropped the Chitka Point Formation down on the north side. It is not certain on which side of the fault this site lies, but submarine topography suggests it is on the up-thrown side. Irregular knobby sea-bottom topography and small offshore islands composed of sub-aerial Chitka Point columnar lavas around the western half of the island suggest that sea level may have been relatively as much as 80 or 90 m lower than at present.

The climate during Chitka Point time must have been considerably less severe than the present climate. Laharic breccias, conglomerates, and bedded tuffs contain remnants of large trees and wood fragments in various stages of silicification.

Pollen from a thin coaly seam identified by E. B. Leopold (Carr, Quinlivan, and Gard, 1970) indicates that such trees as cypress, yew, pine, alder, spruce, birch, poplar, hickory, and walnut were present. She reported that "the sample count contains 6.5 percent of deciduous broadleaved trees now exotic to Alaska, and about a fifth of the generic list includes forms foreign to the region"

Many of the Chitka Point lava outcrops are long, narrow, thick remnants of valley-filling flows which now form ridges such as Column Ridge (Fig. 15) and Andesite Point, suggesting that considerable erosion was concomitant with construction of the volcanic complex. Resistant narrow submarine ridges extending offshore as deep as 90 m below sea level are probably extensions of

Fig. 15—Column Ridge formed by lava flow that filled a valley cut in pyroclastics of the Chitka Point volcanic complex. Differential erosion has removed pyroclastics and left lava flow as a ridge. Cliff is about 100 m high.

these flow remnants. Mex Island (Fig. 7) is a Chitka Point andesite flow remnant that fills a small valley cut in basaltic breccia of the Banjo Point Formation, and a submarine ridge extends offshore from it for a distance of 11 km.

Pliocene Epoch

During and after Chitka Point volcanism, the area of Amchitka Island appears to have remained above sea level. Two periods of minor intrusive activity occurred during the Pliocene Epoch. Small basaltic dikes and sills crop out on the eastern half of the island and were also found mainly intruding the Banjo Point Formation in the exploratory drill holes. Potassium–argon dates on two basalt dikes are 8.9 ± 0.6 and 10.2 ± 1.1 million years (Carr, Quinlivan, and Gard, 1970). If these intrusives had broken through to the surface, nearly all evidence is now gone; however, one small outcrop of what appears to be a basalt flow remnant and an accompanying flow breccia is located at Cyril Cove. A swarm of hornblende andesite dikes

intrudes rocks near the eastern end of the island. Crosscutting relationships between a hornblende andesite dike and a basalt sill at St. Makarius Point indicate that the hornblende andesite intrusives are younger than the basalt.

Pleistocene Epoch

Graben faulting has preserved a rather remarkable series of Pleistocene deposits on Amchitka Island. Sediments are preserved at and near South Bight, at Constantine Harbor, and along the Rifle Range fault. Although the Pleistocene history is far from completely known, these strata reveal more than has been reported so far from any other Aleutian Island. Evidence is found for at least two glaciations separated by a fossiliferous marine deposit.

Marine transgressions during interglacial times have carved at least four well-developed marine terraces (6 to 9, 15 to 18, 37 to 49, and 67 to 76 m) on Amchitka Island (Fig. 3), the latter two of which are warped, tilted, and faulted and are

correlated with fossiliferous marine and beach deposits. Marine regressions during glacial advances have cut one broad extensive terrace (−91 m) and at least two smaller discontinuous terraces (−46 and −77 m) which are now below sea level. Only the −46- and −91-m terraces are extensive enough to be shown on Fig. 3.

Marine terraces are much better developed on the eastern half of Amchitka Island because pre-Chitka Point erosion and beveling had already reduced the rocks of earlier Tertiary age to a low surface. On the steep flanks of most of the western part of the island, Pleistocene terraces are restricted to narrow discontinuous ledges.

Fossil sea cliffs and terraces generally are better developed on the south side of Amchitka than on the north. This same phenomenon holds true for the Holocene tide-level bench (Fig. 8), which is better developed along the Pacific coast than it is along the Bering coast of the island. I believe this is mainly because the southern exposure to the low winter sun allows more thawing and freezing to take place on the south-facing Pacific cliffs during the winter months when the sea cliffs are commonly ice coated than on the north-facing Bering cliffs, which are continually in the shade. Possibly, too, Pacific storms are stronger and generate larger, more powerful waves which would aid in more rapid removal of frost-riven rubble. Fraser and Barnett (1959, p. 240) also noted the better development of the modern tide-level bench on the south side of Kanaga Island, but they attributed it mainly to the southward tilting of that island, which would favor water-level and subaerial weathering.

Early Pleistocene Lake. The South Bight graben was once a closed depression which, in early Pleistocene time, formed a quiet tree-flanked lake along what is now the south shore of the island. Since then, coastal erosion has destroyed the south- and west-bounding bedrock shores of the lake, leaving a cross section of the sediments deposited in the subsiding graben exposed in the sea cliff at the head of the bight (Fig. 16).

The earliest Pleistocene record to be found consists of more than 80 m of tilted and faulted lake sediments exposed in the lower part of the sea cliff (Fig. 17). The beds, mainly of carbonaceous clayey silt and sand, record graben subsidence and, mainly, quiet water conditions.

Thin beds of angular boulders and logs extend into the lake sediments from the north shore, recording times of graben subsidence and sloughing of debris from the north-bounding fault scarp. The boulder beds extend laterally into the lake beds for about 30 m from the fault, and this subsidence event is marked farther out from shore by a

stratum of logs. Four such beds have been noted in the exposed section of lake beds. The graben block must have been subsiding evenly during this time since no angular unconformities have been observed in the fine-grained lake beds. Evenness of the bedding suggests that the lake was deep enough that the bottom sediments were not disturbed by wave action. In the upper half of the section, however, a slight erosional unconformity overlain by 35 m of cross-stratified sand and strongly iron-stained weathered pebble gravel records changed conditions. Whether this deposition records uplift nearby or whether it is outwash from an early glaciation is not known. Subsequently, the graben again reverted to quiet lacustrine conditions for a short time, and 3 m more of carbonaceous sand and silt were deposited.

The lacustrine strata in the lower part of the sea cliff contain freshwater diatoms, pollen, carbonized logs, and wood fragments. Thin ash layers tell of intermittent eruptions of nearby volcanoes. Spruce, pine, and, perhaps, alder grew on Amchitka at this time, and ferns dominated the local vegetation. The pollen assemblage "suggests that the average July temperatures were 2 or more degrees C warmer than now in July. These samples could be either Pliocene or early Quaternary age, and of these an early Quaternary age seems more likely" (Leopold, 1970). The presence of trees suggests that this lake may have existed during the early Pleistocene before the advent of glaciation.

These lower Pleistocene beds may correlate with carbonaceous conglomerate and tuff layers on Tanaga Island which contain a similar pollen assemblage (Fraser and Barnett, 1959, Table 1, locality 14).

South Bight I Marine Transgression. Overlying the lacustrine deposits with apparent conformity, as much as 18 m of even-bedded marine sand and gravel (Fig. 17) provides the first record of a Pleistocene interglacial rise of sea level at Amchitka. This event is referred to as the South Bight I marine transgression.

The lack of evidence of current or wave action in the sands at South Bight and the general fine-grained aspect of the deposit suggest that the sea-level rise was swift and the lake in the graben was overwhelmed and transformed into a closed sea-bottom depression lying offshore. Initially, gravel and then sand were trapped in the depression. The sand contains unworn delicate dichotriaene spicules of a siliceous tetraxial marine sponge (Finks, 1972). Although these sponge spicules are not diagnostic of age, water depth, or temperature, according to Finks they do indicate the sediment is marine.

Fig. 16—Sea cliff at South Bight. Lake beds of early Pleistocene age (1) form lower part of cliff at left (north) and are conformably overlain by South Bight I interglacial marine deposits (2). Both are tilted and faulted (3) and beveled (4). Unconformity (4) has been tilted down to south (right) and is overlain by South Bight II interglacial beach deposits. Sea cow localities are at (5). White sand bed above unconformity at right of picture is composed of cross-stratified shell fragments.

Fig. 17—Diagrammatic geologic cross section of South Bight graben, Amchitka Island. Faults are generalized in part. Vertical exaggeration, 2 X.

A thin deposit of very coarse gravel lies at an altitude of 65 m on a prominent marine terrace about 1.5 km northwest of South Bight (Fig. 4); sand in this deposit contains worn and broken sponge spicules. The base of the abandoned sea cliff of the terrace lies between 67 and 76 m above present sea level (Figs. 3 and 4). I consider this terrace to be related to the South Bight I marine transgression and the gravel to be the remnant of a bouldery beach deposit of the same age. A thin fossiliferous marine deposit cropping out in the cliff at the northwest corner of Constantine Harbor is tentatively correlated with the South Bight I marine transgression and is discussed in more detail later in this chapter.

The South Bight I marine transgression is clearly older than the overlying South Bight II transgression, but at present I am unable to correlate it with marine transgressions recorded on the coast of mainland Alaska.

The South Bight I marine deposit and the underlying lacustrine deposit in the South Bight graben have been tilted southward and broken by a myriad of small faults generally of less than 3-m displacement.

South Bight II Marine Transgression. After tilting and faulting, both earlier deposits were beveled by a new eustatic high-level stand of the sea—the South Bight II marine transgression. This high-level stand of the sea must have persisted for a considerable length of time, for it cut a widespread terrace whose sea-cliff base now lies between 37 and 49 m above present sea level (Figs. 3 and 4). Continued uneven subsidence of the South Bight graben lowered and tilted the unconformity southward and preserved a 6- to 30-m-thick wedge of highly fossiliferous coarse sand to boulder beach gravel that was deposited on the unconformity (Fig. 17).

Activity of nearby volcanoes is recorded by beds of pumice pebbles. Pumice fragments apparently floated to this area, were rounded by wave action and were stranded on the interglacial beach.

This beach deposit contains both vertebrate and invertebrate fossils as well as fossil coralline algae. Uranium-series dating of bone and shell material yielded a preliminary age of about $135,000 \pm 12,000$ years for this deposit (Gard and Szabo, 1971). Further refinement of this date indicates an age of $127,000 \pm 8,000$ years (Szabo and Gard, 1975). A recent study of the rich invertebrate fauna provides evidence for paleotemperatures and paleoecology. Allison (1973) reports that the mean February water temperature probably was about 3.9°C and the mean August sea temperature was between 10.0 and 11.7°C ; these

are similar to present-day temperatures of 3.9°C for February and 10.0°C for August.

Remains of four marine mammal taxa have been found in this deposit. These are Steller's sea lion (*Eumetopias* cf. *E. jubata* Schreber), walrus (*Odobenus rosmarus* Linnaeus), whale, and Steller's sea cow (*Hydrodamalis gigas* Zimmermann) identified by G. E. Lewis and F. C. Whitmore, Jr. (Gard and Szabo, 1971).

The Amchitka fossil is the first recorded discovery of Steller's sea cow remains in place in Pleistocene deposits (Gard, Lewis, and Whitmore, 1972). The giant beast, now extinct, was discovered in 1741 by the German naturalist G. W. Steller along the coast of Bering Island, one of the Komandorskie Islands, the most westerly islands in the Aleutian chain. The sea cow, whose closest living relatives are the manatee and dugong, probably had survived the onslaughts of hunting man only because the islands were unknown to man until the Bering expedition was shipwrecked there in 1741. After that it was only a matter of time—27 years—until these huge sluggish beasts were slaughtered to extinction. They were easy to catch and good to eat, and Russian ships regularly stopped there for victualing.

Parts of the skeleton of a young but apparently nearly full-grown individual, as well as parts of two others, were found in the deposits of the South Bight II marine transgression (F. C. Whitmore, Jr., and L. M. Gard, Jr., 1974). The Pleistocene animal was toothless, as was his eighteenth-century counterpart, and undoubtedly also subsisted on kelp. The South Bight specimen is indistinguishable from the modern species although it was probably somewhat larger. A female specimen found at Bering Island was measured by Steller and found to be 7.5 m (25 ft) long and was estimated to have weighed as much as 10 metric tons (22,000 lb) (Scheffer, 1972).

Powers, Coats, and Nelson (1960) were first to recognize the South Bight II deposit as Pleistocene. They speculated that it was "probably interglacial, and perhaps the youngest interglacial age, inasmuch as the deposit has not been removed by erosion."

Although others have suggested various pre-Illinoian ages for this deposit (Hopkins, 1967; Allison, 1973), mainly on the basis of faunal assemblages, my conclusion is that these beds and the 37- to 49-m terrace were constructed during the last major interglaciation, the Sangamon. This conclusion is based on the extensiveness of the terrace, the freshness of the deposit, and the radiometric age date of $127,000 \pm 8,000$ years, which is roughly equivalent to dates accepted elsewhere for the age of the Sangamon Interglacia-

tion (Richmond and Obradovich, 1972; Mesolella et al., 1969; Szabo and Rosholt, 1969; Birkeland, Crandell, and Richmond, 1971).

The widespread nature of the terrace suggests that the high-level stand of the sea persisted longer than would have been likely during substages of the Wisconsin Stage. It is even less likely that the deposit is as old as pre-Illinoian age. A recent fission-track date of 600,000 years for ash beds in late Kansan or early Yarmouth deposits in the western United States seems much too old for the age of the South Bight II deposit as determined by the uranium-series method. Age-dating methods, as a whole, are susceptible to continuing refinements, however, and many of the "absolute" dates now existing doubtless will be modified in the future.

Other Subaerial and Submarine Terraces. Two brief high-level stands of the sea cut small subaerial terraces at 15 to 18 m and 6 to 9 m above sea level on Amchitka. The terraces are discontinuous but at places have well-developed sea cliffs that are best manifested at Rifle Range and Omega Points (Fig. 4). No deposits or fossil records have been found associated with either terrace; their undissected surfaces and sea cliffs suggest that they are quite young. They may represent brief high sea stands during two of the substages of the Wisconsin Stage. Carbon-14 dates of 9810 ± 160 years on a soil lying at 5 m above sea level near Silver Salmon Lake (Black, 1972) and 8500 ± 350 years (measurement made by Meyer Rubin, U. S. Geological Survey laboratory sample W-2660) for a peat sample 2.6 m above sea level at Rifle Range Point provide a minimum age for the lower terrace.

Powers (1961) has suggested that a small marine terrace is present at 3 to 5 m above sea level on islands in the Aleutians and elsewhere around the Pacific Ocean. Although scattered remnants of flat surfaces at about this altitude are found at the mouths of some streams on Amchitka, it is debatable whether these were surfaces formed by a high-level stand of the sea or whether they are merely related to storm berms.

Pleistocene southward tilting of the island segment lying between Constantine and South Bight grabens is indicated by variations in altitude of abandoned sea cliffs (Fig. 4). The South Bight I terrace is tilted southward more than 6° , but the South Bight II terrace is tilted less than 0.5° to the south. Tilting of this segment started before cutting of South Bight II terrace and continued after it was formed. The lack of tilting of the lake sediments trapped in the South Bight graben before deposition of the conformable overlying South Bight I beds suggests that tilting of the island block probably did not start until after South Bight I time.

Sea level is believed to have been relatively stable for the past 2000 to 4000 years, on the basis of the presence of a broad intertidal bench (Fig. 8) found at many places around Amchitka and other Aleutian Islands (Morris and Bucknam, 1972). Such geomorphic evidence indicates that, despite the high seismicity of the Aleutian arc, most of the islands have remained isostatically stable during this time, although abandoned sea cliffs on some of the Delarof Islands lying east of Amchitka Pass suggest that several meters of uplift may have occurred there during the past several thousand years (Morris and Bucknam, 1972).

During the glacial advances sea level was considerably lower than at present because large volumes of water were stored in massive continental glaciers. Detailed bathymetric charts indicate several submerged marine terraces around Amchitka Island. The two that are best developed are shown in Fig. 3. The largest of these is quite extensive and is found on both the Bering and Pacific sides of the island. It consists of a smooth, almost featureless platform lying between -91 and -100 m and is as much as 4.8 km wide on the Pacific side of the island. Other less well developed submarine terraces lie at about -46 and -77 m (not shown in Fig. 3). Other smaller submarine terraces doubtless are present, but the lack of density of soundings, especially near shore, prevents adequate delineation of such features.

The width and continuity of the -91-m submarine terrace suggest that it may have been formed by more than one marine regression. Although minor tilting and faulting of abandoned subaerial sea cliffs are recognized, no large variations in the altitude of the -91-m terrace is apparent. Perhaps this is due to a lack of density of bathymetric soundings, but it does suggest that tectonic warping of this segment of the Aleutian Ridge was minimal during the Pleistocene epoch. In the Delarof Islands group, south to southwestward tilting of marine terraces and minor Holocene uplift have been recognized (Morris and Bucknam, 1972). When sea level was at -91 m, Amchitka, Rat, and Kiska islands were part of one large island, which was 165 km long and varied from 5 to 50 km in width.

Other Pleistocene Deposits. Glacial till and outwash are rare on Amchitka and, like the interglacial deposits, are generally restricted to topographically low, protected areas. Hummocky sea-bottom topography associated with closed depressions suggests that glacial deposits lie offshore in greater quantity. The most extensive subaerial deposits are found in Constantine graben and north of the Rifle Range fault. Till less than 0.5 m thick

and scattered faceted and striated boulders overlie the South Bight II beach deposit at South Bight.

On the north side of the Rifle Range fault, a deposit of probable outwash sand and gravel of unknown age, which is broken by several small faults, is overlain by scattered faceted and striated glacial erratics.

Two till-like sheets (or diamictites*) of distinctly different ages crop out in the cliff at the northwest corner of Constantine Harbor. Little can be said concerning the age of the older deposit except that it is probably pre-Wisconsin. This is the only evidence found on Amchitka of an older episode of glaciation. The deposit is extremely well indurated, displays rude stratification, contains discontinuous chaotic sandy beds, some weathered cobbles, and many faceted and striated cobbles and boulders. It is overlain by a shallow-water fossiliferous marine deposit, which, in turn, is overlain by Wisconsin till or diamicton. The older diamictite and the marine deposit have been offset as much as 20 m by a fault.

The marine deposit, presumably interglacial, cannot be correlated with certainty with either of the interglacial deposits at South Bight. It contains a small poorly preserved assemblage of shallow-water pelecypods (Addicott, 1972) and sponge spicules. One of the pelecypods, *Macoma nasuta*, has never been found in Pleistocene marine transgressive deposits on mainland Alaska (Hopkins, 1967), nor has it been found in the deposits of the South Bight II marine transgression on Amchitka (Allison, 1973). Induration, iron staining, pebble weathering, and leaching of carbonate in the fossil shells suggest, however, that this deposit is quite old. Its position beneath a diamicton thought to be of Wisconsinan age indicates that it predates that deposit. The presence of sponge spicules, which, so far, are found only in deposits of the South Bight I marine transgression, suggests that these marine beds might be correlative with the South Bight I deposit. Admittedly, this is a very tenuous correlation since the sponge spicules have a wide-ranging age. If these shallow-water deposits are of South Bight I age, however, they either have been down-faulted at least 50 m, or, more likely, they were deposited sometime during advance or retreat of the South Bight I transgression. If the *Macoma*-bearing beds are of South Bight I age, then the

*A nongeneric term for nonsorted or poorly sorted, noncalcareous, terrigenous sedimentary rock that contains a wide range of particle sizes in a muddy matrix. Diamicton is the nonlithified equivalent. The terms are used here because the rude stratification in these deposits suggests the influence of moving water during their deposition and that they may not have been deposited directly by ice. Lack of disturbance of the lake deposits underlying the diamicton shown in Fig. 18 tends to strengthen this argument.

subjacent diamictite must be very old—at least Kansan in age.

A widespread but probably thin ice cap deposited a sandy, stony diamicton less than 2 m thick upon the marine deposit and older diamictite and throughout much of Constantine graben where ice has striated bedrock and deposited extensive sandy and silty outwash and ice-front pond deposits under the diamicton (Fig. 18). In Constantine graben these outwash deposits are tilted southeast and, in places, are broken by many small faults. A thin clayey till interbedded in the outwash on the north side of the graben, and in fault contact with Constantine fault on the south side of the graben, probably represents direct deposition from the ice. In most places this glacier left only randomly scattered faceted and striated erratics.

This younger glaciation is not directly dated, but we may speculate on a minimum age based on carbon-14 dates. The oldest dates on peat or organic soil on Amchitka are on the order of 9000 to 10,000 years B. P. (Everett, 1971; Black, 1972). A carbon-14 date of 8090 ± 300 years (measurement made by Meyer Rubin, U. S. Geological Survey, laboratory sample W-2849) was obtained from a 15-cm-thick undulating soil overlying about 1 m of dune(?) sand which, in turn, overlies the younger diamicton. The sample site lies about 550 m inland from Constantine Harbor at an altitude of 17 m. These ages suggest that the island either was not deglaciated or had too harsh a climate to support vegetation again until about 10,000 years ago.

The Quaternary geology of the central and western parts of Amchitka has been studied in less detail, but it must be assumed that a thin ice cap also covered those parts of the island since they are topographically higher than the eastern end. Depositional evidence of glaciation northwest of the Rifle Range fault is rare; erosional evidence in the form of rock-defended lakes lying west of site C (Fig. 2) suggests that that part of the island also was ice covered. In the mountainous western third of the island, glacially eroded U-shaped valleys and cirques indicate that glaciers filled the valleys, but glacial deposits are rare on land. Scattered erratic boulders lie on the high plateau west of the mountain segment. Hummocky sea-bottom topography suggests that these glaciers may have deposited debris as much as 90 m below present sea level although no distinctive terminal moraine shapes are seen.

Correlation of Amchitka Pleistocene deposits with other Pleistocene deposits and marine transgressions on mainland Alaska or with classical Pleistocene sections of the Midwestern United States or Europe is for the most part tenuous at

Fig. 18—Rhythmically bedded glacial-pond deposit of alternating sand and silt overlain by 2-m-thick diamicton of unsorted stony clayey sand. Weathered surface of diamicton at right shows faint trace of layering, which suggests that it may not have been directly deposited from melting ice. The dark band at top of face is peat containing thin ash layers. The shovel at lower right is about 1.3 m long.

best. On mainland Alaska pre-Wisconsin (Illinoian?) glaciation was far more extensive than that of the Wisconsin (see, for example, Alaska Glacial Map Committee of the U. S. Geological Survey, 1965). It appears, however, that, although this same relationship may have also occurred on the western Alaska Peninsula and in the Aleutian Islands, Wisconsin glaciers were extensive enough to have covered most of what is now land surface and to have removed most evidence of the pre-Wisconsin glaciation. For example, on the western Alaska Peninsula, the Cold Bay area is reported to have been covered by an asymmetrical ice sheet that centered on the continental platform south of the Aleutian Range (Alaska Glacial Map Committee of the U. S. Geological Survey, 1965; Funk, 1973). On Umnak Island in the eastern Aleutians, early studies by Byers (1959, p. 349) suggested that extensive glaciation of the Nikolski plain "was late Pleistocene, possibly Wisconsin in age". Extensive Wisconsin glaciation on Umnak is further substantiated by Black (1972), who states that "no glacial deposits have been recognized earlier than late Wisconsinan when an extensive ice sheet

covered all but the highest peaks until 10,000 or 11,000 years ago." In the western Aleutians, Schafer (1971, p. 788) recognized that extensive ice sheets, which he suggests were "no older than Wisconsinan," covered the Near Islands (Attu, Agattu) and the Semichi Islands.

The lack of peats or soils yielding carbon-14 dates older than about 10,000 years, not only on Amchitka Island but also on 13 other islands from Kiska in the west to Tanaga in the central Aleutians strongly suggests that ice caps or permanent snowfields must have covered these islands during late Wisconsinan time. According to Black (1972), "the lack of soils older than 10 or 11 thousand years seems universal from the Alaska Peninsula westward at all points I have seen. If the islands were not covered by ice, then I dare say a periglacial climate brought extremely rapid mass movements [of colluvium]. This does not seem defensible, however, because I at least have not found any massive accumulations [of colluvium] in low areas."

Thus, evidence from other islands at the extremities of the Aleutian chain supports the

findings on Amchitka that an ice sheet of Wisconsinan and probably late Wisconsinan age covered Amchitka Island.

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Hydrology

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Amchitka Island is composed of stratified volcanic rocks that vary widely in hydraulic properties. Because of the low interstitial permeability in most of the rocks, groundwater moves most actively in the upper few hundred meters where fractures in the rocks are numerous and more open. Together with the thick surficial mantle of vegetation and peat, the shallow aquifers comprise a groundwater reservoir that responds strongly to infiltration of precipitation. Flows of most streams and levels of many of the lakes are sustained during dry periods by discharge from the shallow groundwater system. Direct surface runoff of precipitation occurs frequently, however, and the quality of the surface water during these periods is influenced by salt spray from the oceans.

Hydraulic tests and temperature measurements in deep drill holes show that the hydraulic head decreases with depth beneath the island. The rocks have sufficient permeability to permit slow downward flow of small amounts of fresh groundwater in response to this gradient to estimated

depths of more than 1000 m where it then moves laterally and upward along an interface with saltwater to discharge at the ocean floor.

The collapse of the cavity produced by the Cannikin nuclear explosion created an unsaturated rubble chimney and an area of surface subsidence now filled with water and known as Cannikin Lake. Both surface runoff and flow from the shallow groundwater system were captured for more than a year to fill the chimney voids and the lake basin. The lake and rubble chimney may have almost doubled the depth of fresh groundwater flow, allowing circulation into the rubble-filled explosion cavity. If the hydraulic properties determined by testing in the exploratory hole at this site are similar to those along a hypothetical flow path, it is estimated that water presently in the cavity could discharge to the Bering Sea within 100 years. The rate of the discharge to the Bering Sea would be extremely small, about 20 m³/day.

Amchitka Island has an area of about 300 km² (Coats, 1956, p. 86). Altitudes on the island range from sea level to 350 m (1160 ft), and the estimated average altitude is 85 m (280 ft). The topography consists of varied landforms, including mountains, a high plateau, lower plateaus, and an intertidal bench (Gard, Chap. 2, and Everett, Chap. 8, this volume). Except for the steep-sided rugged mountains on the northwest end of the island, most of the land surface has a rich growth of alpine-zone mosses and grasses. The island is transected by many faults (Gard, Fig. 2, Chap. 2).

The U. S. Geological Survey has performed hydrologic studies on Amchitka Island since 1964. A long-term hydrologic monitoring network was established in 1967 to document the effect of nuclear testing on the island. Prior to these investigations, little was known about the hydrology of the island.

Hydrologic studies on Amchitka have been concentrated in the central part of the island bounded by Sites B and F (Fig. 1). The data acquired from surface-water studies and from groundwater studies in a few deep exploratory

holes and in several shallow holes are used here to describe the hydrology of the island.

SURFACE WATER

There are many streams and lakes on Amchitka Island. The drainage basins for the streams are relatively small, usually less than 2.6 km² (1 mile²). Gaging stations were established to measure discharge on five of the larger streams near potential explosion sites. Records of monthly precipitation at the airport [67.0 m (220 ft) above mean sea level] (Fig. 1) were collected from October 1967 through June 1972.

Stream Runoff and Precipitation

Greater discharge is associated with streams having basins at higher altitudes than with those in the lowlands of southeastern Amchitka Island. This relationship was tested by comparing average drainage-basin altitudes with distributed annual runoff, expressed as the depth of water (in millimeters) that would occur if the total volume of annual runoff were distributed over the area of

Fig. 1—Hydrologic monitoring points and site locations, Amchitka Island.

the drainage basin. Average basin altitudes and drainage areas were determined from topographic maps. Results of the comparison, using discharge records for calendar years 1969 and 1970 (U.S. Geological Survey, 1970, 1971, and 1972) at Bridge Creek, Falls Creek, and Limpet Creek (Fig. 1), are as follows:

Drainage basin	Average altitude, m	Distributed annual runoff, mm
Bridge Creek	38.4	598
Falls Creek	74.4	949
Limpet Creek	88.7	1198

Figure 2 shows these results. The average annual precipitation at the airport of 953 mm (37.5 in.) for almost 5 years of record (Armstrong, Chap. 4, this volume) is also plotted against the altitude of the gage. These data indicate that distributed runoff, and thus precipitation, does increase with altitude. Furthermore, the comparison of precipitation at the airport with the runoff–altitude relationship in Fig. 2 indicates that most of the precipitation results in surface-water runoff.

Stream-discharge records collected during dry periods and between storm periods show a base

streamflow sustained by groundwater discharge (Figs. 3 and 4). Figure 3 shows the base flow of Falls Creek gradually declining during May and June 1968, a period of little precipitation, as water in the surficial materials and underlying bedrock was depleted. The increases in discharge in July and August are small in relation to the corresponding increases in total volume of precipitation, which is estimated by multiplying the daily precipitation at the airport (the only point at which

Fig. 2—Distributed annual stream runoff (January 1969–December 1970) and average annual precipitation at the airport (October 1967–June 1972) versus altitude. Airport precipitation from Armstrong, Chap. 2, this volume.

Fig. 3—Discharge and estimated precipitation in Falls Creek drainage basin, April through September 1968.

Fig. 4—Discharge and estimated precipitation in Falls Creek drainage basin, October 1968 through March 1969.

long-term data were collected) by the area of the Falls Creek drainage basin. The difference indicates that the surficial materials and underlying bedrock had to be resaturated by recharge from precipitation before discharge increased in September. Precipitation and discharge (shown in Figs. 3 and 4) may not always coincide because of the 22-km distance between the precipitation and streamflow gages.

lost all their water through evaporation and infiltration. Through this period some deeper lakes, such as Pumphouse Lake, Long Lake, and Jones Lake (Fig. 1), which occupy bedrock depressions and are apparently fed by perennial springs, continued to discharge water to streams.

Cannikin Lake. Cannikin Lake (Fig. 5) is unique among the many lakes on the island

Fig. 5—Cannikin Lake and White Alice Creek drainage basin. Modified from Gonzalez et al. (1974).

Lakes

Hundreds of small shallow lakes dot the landscape on Amchitka, especially on the marine terraces on the eastern two-thirds of the island. These lakes range in width from less than 30 m to more than 100 m and in depth from less than 1 m to more than 3 m. Lakes in the mountainous areas occupy bedrock depressions; lakes in the southeast part of the island are more numerous, however, and most are confined entirely by the thick vegetation and peat. These lakes occupy depressions in the peat and have bottoms composed of organic material, silt, and clay of low permeability. During rainy seasons water flows from the lakes and intermittent springs, but during dry seasons many lakes and springs become dry. May and June 1968 was a dry period during which many lakes

because it fills the surface depression that resulted from the collapse of the cavity formed by the Cannikin nuclear explosion. Figure 6 is a photograph of the lake taken in May 1974. This lake is one of the largest and the deepest on Amchitka. It has a surface area of 12 ha (30 acres), a depth of about 10 m (33 ft) at its deepest point, and a volume of $4 \times 10^5 \text{ m}^3$ ($1.4 \times 10^7 \text{ ft}^3$) (Gonzalez, Wollitz, and Brethauer, 1974).

The Cannikin nuclear device was detonated at a depth of 1791 m below land surface on Nov. 6, 1971. The explosion cavity, which collapsed 38 hr after detonation, formed a near-vertical rubble chimney extending to the land surface. The collapse at the surface formed a closed depression with associated fractures and faults centered about 360 m southeast of ground zero. (For a discussion of the asymmetry of the collapse, see Morris, Gard,

Fig. 6—Aerial view of Cannikin Lake.

and Snyder, 1972.) This closed depression captured surface-water discharge from 84% of the surrounding (White Alice Creek) drainage area (Gonzalez et al., 1974).

The rubble chimney created a hydraulic sink, and groundwater flowed toward and infiltrated the chimney. The decline in groundwater level around the site also induced infiltration of surface water. Except for small ponds, no visible filling of the surface depression occurred for more than 10 months after the chimney collapsed.

The closed subsidence depression began to fill in September 1972, which indicates that the infiltration rate changed significantly that month. Gonzalez et al. (1974) deduced that the rate change was caused by the saturation of the rubble chimney. By December 1972 the surface depression had filled and had begun to overflow into the lower reach of White Alice Creek and thence to the Bering Sea. After Cannikin Lake had filled, discharge records (Fig. 7) show that White Alice Creek again responded normally to precipitation, which also indicates that the rubble chimney was saturated.

Chemical Quality of Surface Water

The water in streams, lakes, and springs on Amchitka Island is of excellent quality, generally

containing less than 200 mg of dissolved solids per liter. Sodium (Na^+) and chloride (Cl^-) are the dominant cation and anion, respectively. In terms of reacting-value percent (100 times milliequivalents of ion per liter divided by total milliequivalents of cations or anions per liter), Na^+ constitutes about 70% of the cations and Cl^- about 52% of the anions. The relative concentrations of both of these ions are greater than those generally found in continental surface water or precipitation, which indicates that the quality of precipitation on Amchitka Island is strongly influenced by salt spray from the nearby Pacific Ocean and Bering Sea.

Chemical characteristics of water from sources on Amchitka Island and various other sources of interest are given in Table 1 for comparison. Examples of the chemical character of precipitation in continental areas are given for rainfall in North Carolina and Virginia (A in Table 1) and for low-conductance water from European Alpine lake (B in Table 1). The data for A and B contrast markedly with those for oceanic water (C in Table 1) and, in terms of the ratio Na^+/Cl^- , with those for precipitation in the Pacific Ocean (D in Table 1). The Pacific Ocean samples were collected during September 1961 on the flying bridge of the U.S. Coast and Geodetic Survey ship *Pioneer*

Fig. 7—Discharge at the White Alice Creek gaging station, October 1971 through February 1973.

between latitudes $25^{\circ}25'N$ to $51^{\circ}45'N$ and longitudes $177^{\circ}02'W$ to $177^{\circ}31'W$.

Several samples of precipitation on Amchitka Island were taken by collecting drainage from the roof of the airport hanger. Values of the ratio Na^{+}/Cl^{-} for these samples ranged from about 0.9 to 1.3, which possibly indicates variability in salt-spray influence under differing wind conditions.

Sample suites E, F, and G in Table 1 have Na^{+} and Cl^{-} contents (in terms of percent reacting values) that are intermediate between contents of these ions in continental precipitation and in oceanic water. The ratios Na^{+}/Cl^{-} for averages of these samples of Amchitka surface water do not show a clear similarity to oceanic water. In Fig. 8, however, Na^{+}/Cl^{-} ratios are plotted against specific conductances for individual samples. Although the data are scattered, it is evident that samples having lower conductance, i.e., those having dissolved less mineral matter from the island, have Na^{+}/Cl^{-} ratios that closely approach the ratio for oceanic water. This strongly indicates that salt spray does significantly influence the chemical character of precipitation on Amchitka Island.

GROUNDWATER

Groundwater investigations on Amchitka Island were conducted to provide information for assessing the feasibility of mining emplacement chambers for nuclear devices and for evaluating the possibility of migration of radioactive contaminants away from potential sites. The investigation included reconnaissance surface study of hydrologic features (springs, seeps, and perennial lakes and streams), long-term monitoring of water levels in test wells and other available holes, and detailed testing of deep (1000 to 2134 m) exploratory holes at actual and potential explosion sites.

Terminology and Measurement of Parameters

The configuration of the water table is basic to hydrologic investigations. For most practical purposes, the water table is the surface below which all openings in the soil or rock are saturated with water. Because capillary rise may cause fine-grained materials above the water table to be saturated with water at less than atmospheric pressure, the water table is best detected in the subsurface by

Table 1—Chemical Characteristics of Water Samples from Amchitka Island and Selected Other Sources

Sample source and reference*	Percent of cations†				Percent of anions†			Specific conductance‡	Sodium/chloride (Na ⁺ /Cl ⁻)	Number of samples averaged
	Sodium (Na ⁺)	Potassium (K ⁺)	Magnesium (Mg ²⁺)	Calcium (Ca ²⁺)	Chloride (Cl ⁻)	Bicarbonate (HCO ₃ ⁻)	Sulfate (SO ₄ ²⁻)			
Inland precipitation										
A	34.2	3.9	16.2	45.7	22.8	12.9	64.3	<10	1.5	*
Alpine lake										
B	e28.2§	e2.0	7.4	62.4	18.4	65.4	16.2	e45	1.5	Unknown
Oceans										
C	77.2	1.6	17.8	3.4	91.1	0.4	8.5	45,500	0.85	Unknown
Pacific Ocean precipitation										
D								e80 to e500	0.84	5
Amchitka Island										
E (streams)	64.2	2.3	14.7	18.8	55.1	36.5	8.4	237	1.17	14
F (lakes)	81.0	2.7	9.7	6.6	49.7	41.0	9.3	270	1.67	8
G (springs)	71.5	3.9	14.3	10.3	48.5	41.5	10.0	230	1.47	5

*A, average values for 1-year period in five-basin area of North Carolina and Virginia; data from Gambell and Fisher (1966, p. K33). B, European Alpine lake; data from Chebotarev (1955, p. 43). C, data from Ballance and Beitem (1972, p. 10). D, Rain samples collected in the Pacific Ocean on board the USCGS ship *Pioneer*; data collected by F. H. Rainwater and reported by Gambell and Fisher (1966, p. K25). E, F, and G, data from Ballance and Beitem (1972, pp. 10-12).

†100 times ratio of reacting value of individual ion to total reacting values of cations or anions.

‡Micromhos per centimeter at 25°C.

§e, estimated.

Fig. 8—Relation of the ratio Na⁺/Cl⁻ to specific conductance of stream, lake, and spring water on Amchitka Island.

the standing water level in drill holes rather than by laboratory measurements of saturation in soil or rock samples. Springs, streams, and lakes that persist during prolonged dry periods usually indicate intersections of the water table with the land surface and groundwater discharge to the surface-water feature. The configuration of the water table defines the gravity-driven potential field that causes groundwater flow in the saturated zone.

Static head, or simply head as usually applied in groundwater hydraulics, is a measure of potential energy at any point within the groundwater body. It is the sum of the hydrostatic pressure (the height of a column of water that the pressure at the point will support) and the elevation of the given point above a datum, usually chosen as sea level. Rapidly flowing water, a rarity in groundwater, may have sufficient kinetic energy to require the addition of the velocity head to obtain total head. Head measurements at Amchitka were made during the testing of drill holes by isolating intervals at depth with pairs of hydraulically inflated packing elements (straddle packers) and measuring water levels in tubing open to the zone between packers. The hydrostatic component of the head is affected by the density of the water column in the tubing. To provide comparability among measurements at great depth, one must normalize the apparent hydrostatic heads by correcting for the influence of the temperature and salinity on the density of the water column. In this chapter head is expressed as altitude (in meters) above sea level.

Groundwater flows in response to differences in head within the three-dimensional potential field. The hydraulic gradient is a dimensionless

quantity that expresses change of head per unit length of flow path. It is a measure of the rate of consumption of energy required to move water through soil and rock.

The volume of water (at existing viscosity) per unit time passing through a unit cross-sectional area of rock under a unit gradient is the hydraulic conductivity. Permeability is the more common term expressing essentially the same quantity, but, in the terminology of groundwater hydraulics, permeability is a property of the rock as determined with (or corrected to) a fluid having a viscosity of 1 centipoise. When expressed quantitatively, the distinction may be significant; in qualitative expressions, however, permeability and its derivatives are the more easily used terms.

The thickness of a rock unit multiplied by its average hydraulic conductivity is termed the transmissivity. Under field conditions average hydraulic conductivity is determined from measured transmissivity and thickness. The same episodes of straddle-packer testing as those used in measuring static heads were used on Amchitka to determine transmissivity. The usual technique was to swab (remove with rubber lifting elements on wire line) water from the tubing after closing ports that connect the tubing to the interval of hole between the packers. Opening the ports caused an immediate drop of head in the tested interval, and the subsequent recovery of head (water-level rise in the tubing) was analyzed by a curve-matching technique (Cooper, Bredehoeft, and Papadopoulos, 1967) to determine transmissivity. Where a sufficient difference between the land-surface altitude and static head existed, similar slug-recovery tests were performed after the tubing had been filled with water.

Transmissivity is the most important parameter for estimating the sustained inflow that would occur while mining an underground emplacement. For the prediction of the rate of radionuclide migration, however, gradient, hydraulic conductivity, and effective porosity are needed. Porosity is the proportion of the volume of openings to the total volume of soil or rock. Effective porosity includes only that part of interconnected total porosity which, because of its relatively higher hydraulic conductivity, most readily transmits water. Fractures in rock of low to moderate primary permeability most commonly determine effective porosity, and the term fracture porosity is essentially synonymous with effective porosity for such rocks.

The units of hydraulic conductivity (k), volume per unit area per unit time per unit gradient (i), reduce to the units of velocity. Because flow occurs only through the pore spaces, and most

rapidly through the effective porosity (n_e), the particle velocity (v_p) of water for use in predicting contaminant velocity (ignoring retardation by adsorption) is given by

$$v_p = \frac{ki}{n_e}$$

Shallow Groundwater System

The materials in the upper few meters to perhaps a few hundred meters beneath the surface of Amchitka Island are quite permeable and, where unsaturated, are capable of accepting recharge readily. These materials consist of tundra, soil, peat, and fractured and weathered volcanic rocks. The observed strong response of water levels in shallow observation wells to infiltration of precipitation provides evidence of the ease of infiltration. Fluctuations determined by periodic measurements in four closely spaced holes at the Long Shot site (see Fig. 1) are shown in Fig. 9.

Figure 9 also shows that, at the Long Shot site, heads decrease as the depth of penetration increases, which indicates downward flow. The greatest downward hydraulic gradient (about 0.05) occurs between depths of 30 and 90 m, which indicates either an increase in permeability or a reduced vertical (increased horizontal) component of flow at greater depths. For the groundwater to reach points of discharge (streams, lakes, and springs for the shallow aquifers and the coastline or beyond for the deeper aquifers), the initial downward flow must, of course, change to predominantly horizontal or upward flow.

The water table is at or very near land surface over most of the island, as indicated by the many perennial lakes and streams and by water levels in shallow holes. Surficial materials at many places are saturated except for about 2 months of each year when there is usually less precipitation. Consequently the configuration of the water table is essentially that of the land surface, although the water table has less relief than the land. In general, the hydraulic gradient is from the axis of the island toward the coasts. Many seepage points occur along the coasts at the contact of turf and underlying rock or along rock fractures. However, few major springs issue from the underlying consolidated rocks above sea level near the shoreline. This suggests that, although the hydraulic potential exists for oceanward movement of groundwater, the transmissivity of the rocks in the upper few hundred meters is not high enough for large rates of flow. Most groundwater beneath Amchitka apparently moves in very local systems to discharge in the lakes and streams, a conclusion supported by

Fig. 9—Water levels in shallow holes at the Long Shot site.

the earlier observation that most precipitation on the island runs off in stream channels.

In the northwestern part of the island, where the slopes are steep and there are many cliffs, soil and peat are very thin or nonexistent. Water collects in small surface depressions perched above the water table. Some steep stream valleys have benches of accumulated erosional debris (colluvium) made up largely of angular rock fragments. At lower altitudes the surface of this colluvium is covered by soil and a thick mat of vegetation. Recharge from precipitation percolates through the mantle of vegetation and colluvium and flows downslope along the surface of the underlying less permeable volcanic rocks to issue as springs. One such spring supplied a military camp at Top Side (Fig. 1) during World War II.

Hydraulic Characteristics of Deep Rocks

Deep exploratory holes ranging in depth from 1000 to 2134 m were drilled at Sites B through F (Fig. 1). The holes principally penetrated volcanic breccias containing dikes, sills, and beds of poorly sorted volcanic sandstone, siltstone, and tuff. The youngest (uppermost) breccias are mostly submarine turbidites consisting of coarse fragments of volcanic materials often in a sandy to clayey matrix. The older (deeper) breccias generally contain more zeolite and chlorite in the fractures and cavities, which probably reduces the effective porosity and permeability of these rocks. These

varied geologic conditions provide a complex framework for groundwater movement. Because the stratified rock units have greatly differing hydraulic properties, flow in the vertical direction is generally retarded throughout the island.

The exploratory holes at Sites B through F were tested both by pumping and by slug-recovery tests after swabbing water from or injecting it into zones isolated with straddle packers. Sites B and C, the eventual locations of the Milrow and Cannikin explosions, were tested more thoroughly than the others and thus provide the best data on the variation of the head and transmissivity with depth. The zones tested were generally about 60 m thick, although packer spacings were varied somewhat so that packers could be seated in suitably smooth parts of the drill holes.

Transmissivities determined from the packer tests vary over a range of five orders of magnitude, from about $30 \text{ m}^2/\text{day}$ in a 60-m zone centered about 700 m below sea level at Site C to about $0.0003 \text{ m}^2/\text{day}$. Such a range is expected in stratified materials of various origins, mineralogy and mechanical properties.

Figure 10, which is based on measurements reported by Ballance (1972, 1973), shows that at Sites B and C there is a general decrease of transmissivity with depth, although the decrease is far from uniform. Transmissivities greater than $0.1 \text{ m}^2/\text{day}$ in zones deeper than about 1000 m below sea level were observed commonly only at

Fig. 10—Transmissivities determined from hydraulic tests of isolated zones in drill holes at Sites B and C. ? indicates possible bypass around packers during test, causing falsely high values for transmissivity. [Adapted from Ballance (1972; 1973).]

Sites C and E. Site F is the least permeable, no transmissivities greater than about $0.05 \text{ m}^2/\text{day}$ having been measured in 15 intervals tested between altitudes of -211 and -1883 m . However, the interval from -486 to -1468 m was not tested, and the test in the deepest interval (-1886 to -1952 m) showed a transmissivity of about $0.15 \text{ m}^2/\text{day}$. Data obtained at Site D indicated low transmissivities similar to those at Site F.

Results of the hydraulic testing point strongly to fractures (joints and faults) as the primary avenues for fluid movement. The fractures tend to close under greater lithostatic loads at depth. In addition, the development of zeolites and chlorites in fractures in the deeper rocks further impedes the movement of water. Thus the decrease of transmissivity with depth is to be expected. Low transmissivities measured in boreholes may be misleading in fractured rocks, however, because dense but brittle rocks penetrated by the hole may be fractured a short distance away.

Temperatures in Drill Holes

During drilling of the deep exploratory holes, water was used as a circulating fluid through most of the intervals that were later tested hydraulically. The introduction of cold surface water to the deep formations undoubtedly lowered rock temperatures temporarily. In addition, the drill holes provided open pathways for water to move from aquifers of higher head to those of lower head.

Temperature profiles reported by Sass and Munroe (1970) were made in October 1968 at Sites B, C, D, and F. The profiles for Sites B, D, and F (shown in Fig. 11) show a uniform increase of temperature with depth. The rate of increase is about $28^\circ\text{C}/\text{km}$, which is similar to the geothermal gradient in many places in the world. Recovery from disruption of the normal thermal environment by drilling at these sites was probably

Fig. 11—Temperature—depth profiles in drill holes at Sites B, C, D, and F. [Modified from Sass and Munroe (1970).]

completed in less than 1 year; only 4 months elapsed between the completion of testing at Site D and the temperature survey.

However, the profile for Site C, measured about 12 months after the completion of hydraulic testing, indicates cooler temperatures below -400-m altitude and less uniformity than do the profiles from the other sites. This indicates that cool water from shallow aquifers was flowing down the hole and entering deeper rocks in which heads were lower. These data demonstrate that the hydraulic gradient at Site C is downward.

commonly referred to as the Ghyben—Herzberg relationship, after the two independent originators of the concept, W. Badon Ghyben in 1888 and B. Herzberg in 1901. In the Ghyben—Herzberg relationship, a balance of head is assumed to exist at the interface of freshwater and saltwater, the height of saltwater from the interface to sea level exerting the same pressure as a somewhat higher column of less dense freshwater. If specific gravities of 1.000 for freshwater and 1.025 for seawater are assumed, this head balance under static conditions would occur at a depth below sea level (A_i on

Fig. 12—Schematic comparison of positions of the interface between freshwater and saltwater under static and dynamic conditions. (a) Simplified approximation, assuming static conditions. (b) Approximation accounting for flow and head changes with depth.

Deep Circulation of Freshwater

Beneath oceanic islands and coastal areas, fresh groundwater flowing oceanward overlies saltwater that saturates openings in rocks at depth. In the ideal case of an island underlain by homogeneous and isotropic material, the freshwater body assumes a lenticular shape, bounded at its base by a concave-upward surface (Fig. 12). As noted by Todd (1959), the relationship between the altitude of the water table and the depth of the interface is

Fig. 12) equal to 40 times the height of the water table (h) above sea level. The resulting idealized lens takes the form shown in Fig. 12a.

In modern applications of the Ghyben—Herzberg relationship (Todd, 1959), it is recognized that such a lens could not be sustained under static conditions. The actual lens must extend out under the sea floor to provide a discharge area for the fresh groundwater (see Fig. 12b). Furthermore, as the fresh groundwater seeps through the rocks,

the head loss (Δh) due to friction reduces the pressure component of head at depth below that calculated for hydrostatic conditions. Consequently the interface between freshwater and saltwater must occur at a shallower depth than that predicted by the simplified Ghyben—Herzberg relationship, $A_i = -40h$. Finally, the interface is actually a zone of mixed freshwater and saltwater resulting from dispersion, ocean tides, seasonal fluctuations of the water table, and diffusion in response to salinity and temperature gradients.

Effects of Geology and Paleohydrology. Although the distortion of the simplified static lens by dynamic conditions is considered above, the conceptual model of fresh groundwater flow beneath Amchitka Island must be modified further to take into account the geologic framework as well as the hydrologic history of the island.

Downward and upward flow through stratified rock sequences requires large gradients as compared with gradients for flow parallel to stratification in the more transmissive units. Because the strata at Amchitka dip moderately (about 10° to 40° southwestward near Site C), even units that are several hundred meters or more beneath the surface at the center of the island probably intersect the sea floor. This geometric setting implies that most of the head loss in the deep groundwater system occurs during flow in the more-resistant downward direction whereas relatively little gradient is then required to expel the water to the sea through the aquifers. The result is that head declines with depth beneath the island at a greater rate than would be calculated for a homogeneous isotropic system. The actual depth of the freshwater lens, therefore, is less than it would be in the idealized setting.

Sea-level changes cause corresponding changes in the position of the Ghyben—Herzberg interface. However, the hydrology of Amchitka Island is not known in sufficient detail to predict the length of time needed to reestablish equilibrium flow conditions after significant changes in sea level. Gard (Chap. 2, this volume) indicates that sea level varied by probably several tens of meters as varying amounts of water formed ice during advances and recessions of Pleistocene glaciers. The last glacial advance, on the basis of ^{14}C dating of peat (Gard, Chap. 2, this volume), apparently ended about 10,000 years ago when sea level was about 30 m below that at present. For an unknown period before the continental glaciers had begun to melt, sea level was possibly as low as -90 m. As melting began on Amchitka, the potential recharge was probably so great that the water table was at the subglacial land surface, i.e., on the order of 10 m

higher than the present water table, if the land surface was at the same altitude as it is today. If we estimate sea level to have averaged through several thousand years 10 m lower than it is at present, the freshwater head would have been about 20 m greater than at the present. Freshwater circulation beneath central Amchitka might have been as deep as 2500 m. However, Gard (Chap. 2, this volume) indicates that sea level has been essentially at its present level for the past 2000 to 4000 years. Whether the rocks beneath Amchitka are sufficiently impermeable or isolated from the oceans to have resisted adjustment of head to a rising or stable sea level in the past several thousand years is unknown, but intuitively it seems unlikely. A broad zone of mixing, relict saltwater in relatively shallow but impermeable rocks, and relict freshwater in deep impermeable rocks are among the complications that may have been caused by sea-level changes.

Salinity of Deep Groundwater. Samples of the water swabbed from intervals isolated by straddle packers in the exploratory holes at Sites B and C generally increased in salinity with depth of sampling. Dissolved-solids concentrations for these samples, reported by Beetem et al. (1971), are shown and compared with the concentration in seawater (about 35,000 mg/liter) in Fig. 13.

At an altitude between about -1050 m and about -1150 m, the dissolved-solids concentration at Site B reached the maximum observed, about 30,000 mg/liter. Considering that quantities swabbed were probably not sufficient to recover all the water that was injected during drilling, this

Fig. 13—Dissolved-solids concentrations of water samples from drill holes at Sites B and C.

concentration indicates that the interface between saltwater and freshwater is above -1150 m. The uniform concentration of about $21,000$ mg/liter in the interval -800 to -1050 m may indicate water that was either diluted by drilling fluids or was drawn from a natural zone of mixing. These four samples were collected during tests conducted in a 24-hr period before the hole was deepened; the three samples immediately below (between -1150 and -1525 m) were obtained during a similar period a month later, whereas the deepest sample was swabbed after 3 weeks of additional drilling. Therefore the difference in dissolved-solids concentration between the zone -800 to -1050 m and the zones below cannot be considered significant unless it is strongly corroborated by other data.

The maximum dissolved-solids concentration in water samples taken as deep as -1800 m at Site C was only about 12% of the concentration in seawater (Fig. 13). Fresh surface water had been used in drilling the hole, but volumes of water similar to those lost in drilling were pumped from each interval of hole before hydraulic testing. Additional data were obtained in another hole only 35 m away.

The Cannikin emplacement hole at Site C was drilled over a 2-year period beginning near the end of hydraulic testing in the nearby exploratory hole. The emplacement hole, 2.3 m (7.5 ft) in diameter, was drilled with only minor losses of the mud circulant below an altitude of -1000 m. At the beginning of mining a chamber at an altitude of about -1725 m for the Cannikin device, a large inflow of mud, unhardened cement slurry, and water forced remedial measures and hydrologic monitoring. As reported by Ballance and Beetem (1972), the inflow soon cleared. The volume of water pumped from the chamber and attendant tunnels during the following 5 months exceeded 7000 m³. The temperature of the discharge soon stabilized at about 41°C . The specific conductance of the water, about 6100 ± 600 $\mu\text{mhos/cm}$ (at 25°C), remained about the same throughout the period. On the basis of chemical characteristics and temperature, Ballance and Beetem (1972) concluded that the inflow was derived from a zone at about -1650 m altitude. The specific conductance of the water was essentially the same as that of samples from the interval -1590 to -1750 m in the exploratory hole.

That the correlation of chemical data from the two holes is coincidental seems highly unlikely. We conclude that the data shown in Fig. 13 for Site C are substantially correct and that the freshwater lens extends to an altitude of at least -1700 m. The anomalously low dissolved-solids concentration in the sample from -1775 m is thought to be

caused by dilution of the sample from water bypassing the upper packer during swabbing.

Head Relationships at Sites B and C. The correction of heads measured in straddle-packed intervals in the exploratory holes at Sites B and C was based on the salinity data in Fig. 13 and on two sets of temperature data. The maximum temperatures that might have predominated in the zones that are tested are those reported by Sass and Munroe (1970) and shown in Fig. 11. The minimum temperatures, caused by introduction of cold drilling fluids, are those determined in geophysical logs run before episodes of hydraulic testing.

The uncorrected and corrected head data for the two sites are shown in Fig. 14, beginning in the upper right corner of each graph. The uncorrected data show a distinct decrease of head with depth uniformly distributed at Site B but occurring mainly above -450 m at Site C.

Correcting the height of the water columns above the zones tested at Site B to an equivalent height of water at a specific gravity of 1.000 results in a significant increase of head because of the high salinity of the water. At an altitude of -1450 m, the correction is about $+25$ m; corrections for the possible temperature extremes, however, differ only by 4 m at that depth and are negative because water is less dense at temperatures above 4°C . The general downward gradient apparently persists after corrections at Site B, although under both of the extreme temperature assumptions the gradient appears to be slightly upward between -700 and -1050 m.

Because the water swabbed from intervals in the Site C exploratory hole was much less saline than that from Site B, the salinity component of the density correction is small. The temperature corrections dominate and result in corrected heads that are somewhat lower than uncorrected heads. The head values based on the minimum temperatures are believed to be the more realistic for zones below -1600 m because testing immediately followed the drilling of this interval, during which there was a large loss of fluids to the rock. The gradient is small in the downward direction, which is consistent with the temperature profile of Fig. 11.

Relation of Data to Ghyben-Herzberg Theory. Earlier in this chapter the altitude at which a balance of head would exist between freshwater above and saltwater below was expressed as $A_i = -40h$, where h is the corrected freshwater head at the depth of the interface. Because the temperature of the saltwater increases with geothermal gradient (28°C/km as determined from

Fig. 14—Uncorrected and corrected static heads at Sites B and C and altitudes of Ghyben-Herzberg interface as a function of static head. Curve 1, uncorrected static heads. Curve 2, static heads corrected for salinity and maximum temperature. Curve 3, static heads corrected for salinity and minimum temperature.

Fig. 11), a density correction must be applied to the saltwater head also. As shown in Fig. 14, beginning at sea level the uncorrected Ghyben-Herzberg curve expresses the relationship $A_i = -40h$. The corrected curve was computed numerically in 50-m increments of depth and shows an increasing slope with depth. At -1400-m altitude, the slope is -48, whereas at -1800 m it is -52.

In theory the depth of the Ghyben-Herzberg interface should occur at the point of intersection

of the curve expressing the corrected freshwater head with the corrected Ghyben-Herzberg curve. Head measurements (expressed as freshwater) below the depth of intersection, however, should coincide with the corrected Ghyben-Herzberg curve. As shown in Fig. 14, the head data from Sites B and C quite obviously do fall below the Ghyben-Herzberg curve. This is an enigma that apparently can be explained only in terms of inadequacy of data or test methods. Residual head drawdowns of 8 to 12 m in the lowermost zones of both holes, resulting from incomplete recovery from pumping before the swabbing tests, is a possible but too convenient explanation.

If the inconsistency of the data from the deepest zones is ignored, the head data suggest Ghyben-Herzberg interfaces at an altitude of -1000 to -1200 m at Site B and at an altitude of -1100 to -1300 m at Site C. When compared with the salinity data (Fig. 13), this range for Site B is reasonable if we attach significance to the salinity differences between the zone -800 to -1050 m and the zones below -1100 m. Earlier (see section on Salinity of Deep Groundwater) this difference was presented as probably not significant without strong corroboration. The head data do not provide sufficiently strong corroboration because of their inconsistency with theoretical head relationships below the freshwater lens.

There is one physically plausible explanation for the salinity difference at Site B, however. The sample at -720 m (Fig. 13) was obtained from a zone that has a transmissivity of about $3 \text{ m}^2/\text{day}$, a relatively high value for the deep groundwater system (Fig. 10). Tests in intervals at -800 m and -980 m, in contrast, indicated transmissivities that are among the lowest measured. Presumably freshwater can circulate with relative ease only to an altitude between -720 and -800 m. The zone from -800 to -1050 m, shown in Fig. 13 to contain water of apparently intermediate salinity, could reasonably be interpreted as a zone of mixing or diffusion above the Ghyben-Herzberg interface as selected by head criteria.

For Site B we are left, then, with the conclusions that a Ghyben-Herzberg interface does exist at an altitude not lower than about -1200 m, that the zone from about -800 to -1050 m may represent a zone of mixing or diffusion, and that the data are not sufficiently precise to eliminate uncertainties.

The data from Site C are even more perplexing. Figure 13 shows that the pattern of salinity change with depth at Site C, although the water was more dilute, is strikingly similar to that at Site B. Furthermore, in Fig. 14 intersections with the Ghyben-Herzberg line occur at similar depths at

both sites. Finally, an apparent deficiency of head exists below the intersection depths at both sites. Referring again to the discussion on salinity of deep groundwater, however, the salinity of the inflow to the Cannikin chamber so strongly corroborates the salinity data from the exploratory hole that we must conclude that the freshwater lens extends at least as deep as an altitude of -1750 m at Site C. It is possible to speculate that adjustment of the salinity interface has not occurred after deep flushing at a time of lower sea level. Supporting evidence is lacking, however. Quite possibly the head data are misleading, and the salinity data indeed show circulation of groundwater to at least -1750 m altitude.

EFFECT OF EXPLOSIONS ON DEEP GROUNDWATER FLOW

Nuclear explosions as large as Milrow (about 1 Mt yield) and Cannikin (approximately 5 Mt) have significant effects on hydrologic features. A complete discussion of these effects is beyond the scope of this chapter.

Disturbances of streamflow and oscillations of fluid pressure in the groundwater system in response to the Milrow explosion have been described by Ballance and Dudley (1970). Gonzalez and Wollitz (1972) have presented similar data for the Cannikin event and have related hydrologic response to seismic stress and motion. The thermal, hydraulic, and radiochemical processes acting in the Cannikin rubble chimney are described by H. C. Claassen (written communication, 1976).

The reports cited above discuss the relatively transient effects of Milrow and Cannikin. However, the penetration of the rubble chimneys deep beneath the surface of Amchitka Island has disrupted the geologic framework sufficiently that long-term effects on the deep flow system are a certainty.

The movement of water in the deep groundwater system under natural conditions is extremely slow, as indicated by the following four items:

1. Stream runoff is sufficiently great to remove most precipitation from Amchitka Island.
2. Transmissivities measured below altitudes of about -750 m are small as are downward hydraulic gradients.
3. The geologic framework suggests that vertical hydraulic conductivity is extremely small.
4. The dissolved-solids concentrations in samples from below altitudes of -400 m at Sites B and C are an order of magnitude or more greater than the concentrations in surface water and shallow groundwater.

However, if exit paths from the deeper aquifers to the oceans are available, which is probable based on currently known geologic conditions, disruption of the vertical resistance to downward flow by an explosion-produced rubble chimney would increase the depth of active or moderately active flow.

The introduction of a permeable vertical path would also decrease the head loss associated with downward flow. Because of the greater residual head at depth, the Ghyben-Herzberg interface must also move downward. Beneath Cannikin Lake, which now maintains a head at the surface of $+35$ m (115 ft) (Gonzalez et al., 1974), the permeable rubble chimney may allow most of this head to be applied to an altitude of at least -1800 m. From consideration of head relationships alone, the Ghyben-Herzberg interface could be depressed to below -1700 m, or well within the cavity region of the Cannikin explosion. The salinity data suggest that the interface might have been that deep even before the Cannikin explosion. In the altitude range of -1500 to -1800 m, which encompasses the cavity and lower rubble chimney, several zones were tested and found (Fig. 10) to have transmissivities between 0.15 and 0.7 m²/day for 60-m depth intervals.

Data from Site B indicate that the rubble chimney from the Milrow explosion, which was detonated at an altitude of -1178 m in October 1969, opened hydraulic communication to relatively permeable zones at -700 and -1050 m altitude. The explosion cavity is within rock units having transmissivities of 0.04 m²/day or less.

Groundwater Velocity

The possibility of freshwater circulation deep into nuclear-explosion sites makes it necessary to consider the velocity with which groundwater could flow and transport radionuclides from the explosion sites to points of discharge at the surface or on the sea floors. The parameters that must be evaluated to perform the calculations are effective porosity, hydraulic conductivity, and hydraulic gradient. Average hydraulic conductivity can be calculated as the transmissivity divided by the thickness of the interval tested. The data in Fig. 10 show the average hydraulic conductivity of the zones between -1500 and -1800 m to be about 3×10^{-3} m/day.

The hydraulic gradient from the Cannikin site (Site C) to the Bering Sea is the head ($+35$ m) of Cannikin Lake, less the head lost in downward seepage through the rubble chimney, divided by the length of the flow path from the lower rubble chimney to the discharge point. The probable flow-path length is 2500 m, a value chosen from a model presented by Fenske (1972) and consistent

with the geologic setting. If the hydraulic conductivity of the rubble chimney is on the order of 1 m/day, a value comparable to those of a uniform medium-grained sand or moderately fractured massive rocks, the loss of head in downward flow through 1800 m of the rubble would be less than 1% of the total head available. Consequently the average hydraulic gradient over the flow path from the lower rubble chimney to the Bering Sea is about 35 m/2500 m, or about 0.014.

The fracture porosity can be estimated from measured hydraulic conductivity and fracture spacing as observed in drill holes and mined chambers. The most intact rocks beneath Amchitka have fracture spacings of several meters; 10 m can be taken as an upper limit. The measured hydraulic conductivity is consistent with that of a moderately but not highly fractured massive rock; a fracture spacing of 0.5 m is a reasonable estimate for moderately fractured rock. The minimum average spacing—occurring in the basalt breccias penetrated by the Site C exploratory hole (Ballance, 1972)—is on the order of 0.05 m.

Snow (1968) related these parameters in the following equation, converted to units in use here:

$$n_f = 5.9 \times 10^{-4} \left(\frac{k}{d^2} \right)^{1/2}$$

where n_f is the fracture porosity (dimensionless), k is the hydraulic conductivity (meters per day), and d is the fracture spacing in the drill hole (meters).

The solution of Snow's equation for fracture spacings of 0.05, 0.5, and 10 m provides fracture porosities of 6.3×10^{-4} , 1.4×10^{-4} , and 1.9×10^{-5} , respectively. Corresponding average particle velocities are 0.07 m/day for the 0.05-m spacing, 0.3 m/day for the 0.5-m spacing, and 2.2 m/day for the 10-m spacing. The width of openings in a cubic set of uniform fractures, calculated from effective porosity and assumed spacings, would be about 5 μ m for the closest spacing, 23 μ m for the moderate spacing, and 63 μ m for the 10-m spacing.

Snow's (1968) investigations in drill holes to depths of about 120 m at dam sites in igneous and metamorphic rocks indicate that fracture openings greater than 40 μ m would be unusual below 100 m but that there is only a very gradual reduction of average fracture width below the 50-m depth. At depths as great as 1500 m, however, openings greater than 20 μ m must be considered as highly improbable. It is more improbable, however, that the measured average hydraulic conductivity is concentrated in the interstices (between grains or crystals) of the basalts and basalt breccias at that depth at Site C.

The velocity range of 0.07 to 0.3 m/day, which correspond, respectively, to brecciated basalt and moderately fractured basalt, results in estimated travel times of 23 to 103 years over a 2500-m flow path. These estimates are based on the assumption that the hydraulic conductivities measured at depth at Site C are representative of the entire flow path. Since the southwestward dip of the geologic units provides probable intersection with the sea floor, thereby eliminating the need for cross-bed flow, this assumption is reasonable. It seems likely that water carrying the more mobile radionuclides, such as tritium, could begin to discharge on the floor of the Bering Sea within a century and possibly within a few decades.

The downward flow in the Cannikin rubble chimney will keep radioactivity concentrated near the base of the chimney, or below about -1500 m altitude. On the basis of the total transmissivity measured below this depth, the 0.014 gradient would allow this region to be flushed by a flow of about 20 m³/day, a very low rate.

Among the factors that will lower the concentration of radioactivity in the water before discharge to the sea are:

1. Radioactive decay.
2. Adsorption on rock surfaces (except tritium).
3. Dispersive mixing with uncontaminated water in the rubble chimney.
4. Spreading of the contaminant plume, both by dispersive mixing and by divergence of flow lines from the chimney to a probably broad zone of discharge.

Although there are insufficient data to estimate the effects of these processes, the dilution will be large—from a few to probably several orders of magnitude. Further dilution by mixing of the slowly discharging groundwater with seawater will be sufficient that detection of radioactivity in above-background concentrations is considered very unlikely.

A similar analysis of the Milrow site provides comparable results. The moderately transmissive zones below an altitude of -1000 m, which before the explosion were below the freshwater lens, probably are now being flushed by chimney water toward the Pacific Ocean. The overall transmissivity of the zone intersected by the lower part of the rubble chimney is about the same as that at Site C, and the available hydraulic gradient is only slightly less.

CONCLUSIONS

Amchitka Island is drained principally by streams that carry direct runoff and sustained base

flow. The base flow is discharged to the streams and many lakes from a moderately permeable shallow groundwater reservoir. Because the water table is at or very near the land surface over most of the island, the shallow groundwater flow occurs within the tundra, soil, and peat as well as within the upper few hundred meters of underlying volcanic rocks. The quality of the surface and near-surface water is good. Salt spray driven by wind over the narrow island from the adjacent ocean influences the composition of rainfall, as indicated by ratios of sodium to chloride in water of the surface and shallow subsurface systems.

Geologic setting, hydraulic characteristics of the rocks, and the salinity of water within the deep groundwater system provide evidence that groundwater movement under natural conditions is very slow or nonexistent at the depths at which the Milrow and Cannikin nuclear explosions were detonated. The Milrow device was sited within nearly static saltwater below the lens of slowly circulating freshwater whereas Cannikin was probably within the freshwater lens.

Disruption of the rocks by rubble chimneys at both explosion sites is believed to have increased the depth and velocity of freshwater circulation. Although the data are sparse, it is estimated that, within a few decades to perhaps a century, water containing radioactivity from deep in the rubble chimneys will begin seeping slowly onto the ocean floor, where the radioactivity will be greatly diluted by mixing with ocean water.

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Weather and Climate

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Amchitka Island has a pronounced maritime climate. The day-to-day weather is marked by changeability because of the great frequency with which migratory pressure systems pass along the North Pacific storm track. In the absence of significant local effects, such as surface heating and nocturnal cooling, which exert a large influence on weather conditions at a continental location, the Aleutian weather results almost entirely from large-scale pressure systems and their associated weather fronts.

During the summer season fog predominates as a result of the advection of relatively warm, moist air over the colder ocean surface. The air in the air-sea interface layer is cooled to the saturation point, and extensive fog results. The summer fog often persists for days at a time.

The Air Resources Laboratory—Las Vegas (ARL—LV) experience during relatively short periods of residence on Amchitka in connection with Atomic Energy Commission (AEC) activities there bore out my hypothesis that climatological data available from a 5-year period in the 1940s adequately defined the local climate and weather. During most of the period that Amchitka was in use by the AEC, airways weather observations were made by airport control-tower operators during periods of tower operations. These data were not continuous, were not under ARL—LV control, and were not summarized. The control-tower data did, however, substantiate the validity of the earlier climatological data. Except for the solar-radiation data, data given here are from the 5-year nearly continuous weather observations of the 1940s. Table 1 contains general climatological data.

Solar radiation was not measured during military occupation. A pyranometer installed at the airport control tower measured the solar radiation, and the limited data obtained are included.

TEMPERATURE

The moderating effect of the surrounding seas is evidenced by the limited ranges of temperature at Amchitka (Fig. 1). The mean daily range is 3.9°C (7°F) or less in all months, and the annual range of the mean daily temperature is only 9.4°C (17°F). By contrast, a continental station (Saskatoon, Saskatchewan) at approximately the same latitude has an annual range of 36.1°C (65°F).

LOW CLOUDINESS

Clear skies are extremely rare at Amchitka (Fig. 2). Fog or clouds below 2972 m (9751 ft) above the airport elevation (67 m, 220 ft) cover more than half the sky most of the time. Low ceilings (more than half the sky covered) and fog occur with greatest frequency during the summer months. In the other three seasons, brief periods of clearing skies follow the passage of migratory storm systems.

FOG, RAIN, AND SNOW

Figure 3 points up the prevalence of fog during the summer months. The high frequency occurs because the seawater is colder than the air that flows over it. The air is cooled, condensing its moisture.

Although mean annual precipitation at Amchitka is not excessive, 828 mm (32.6 in.) compared with 991 mm (39 in.) for Seattle, precipitation in some form is experienced one-fifth or more of the time in all months, with the most frequent hourly occurrence during the summer months (Fig. 3). The average number of days per month on which precipitation in the indicated amounts is

Table 1—Climatological Data for Amchitka Island, Alaska, from February 1943 Through June 1948*

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual
Temperature, °C													
Record high	7.2	6.1	9.4	8.3	9.4	13.9	18.3	15.0	13.9	10.6	10.6	7.2	18.3
Mean daily max.	1.1	1.7	2.8	4.4	5.6	7.8	9.4	10.6	9.4	7.2	4.4	2.2	5.6
Daily mean	-0.6	0.0	1.1	2.2	3.9	5.6	7.8	8.9	7.8	5.6	2.8	0.6	3.9
Mean daily min.	-2.2	-1.7	-1.1	0.6	2.2	3.9	6.1	7.2	6.1	3.3	1.1	-1.1	2.2
Record low	-8.9	-10.0	-6.7	-6.7	-1.1	0.0	2.2	3.3	2.2	-2.2	-5.6	-5.6	-10.0
Av. No. of days with a minimum of													
<-4.4°C	3	2	2	1	0	0	0	0	0	0	†	1	9
<-2.2°C	12	9	6	2	0	0	0	0	0	0	1	6	36
≤0.0°C	28	24	22	13	3	†	0	0	0	2	10	22	124
Av. No. of days with a maximum of ≤0.0°C	9	6	4	1	0	0	0	0	0	0	1	6	27
Precipitation, mm													
Mean monthly	71	51	33	58	41	25	89	104	74	97	71	114	828
Av. No. of days with													
≥0.25 mm	19	17	13	13	11	13	16	20	16	20	20	20	198
>6.35 mm	4	2	1	2	3	1	4	6	4	5	2	6	40
>12.70 mm	1	†	0	1	1	0	3	3	1	2	1	3	16
Percent of hours with rain	9	11	13	24	28	29	40	41	26	21	23	14	
Percent of hours with snow	18	24	16	9	2	†	†	0	0	1	5	15	
Snow depth at 0800 local standard time, cm													
Av. No. of days with depths of													
≥2.54 cm	17	13	1	†	0	0	0	0	0	0	3	7	41
>5.08 cm	15	10	0	†	0	0	0	0	0	0	2	5	32
>15.24 cm	4	3	0	0	0	0	0	0	0	0	0	1	8
>30.48 cm	1	0	0	0	0	0	0	0	0	0	0	0	1
Surface wind													
Mean speed, m/sec	11	11	11	9	8	7	7	8	8	9	9	11	9
Percent of hours with speed ≥14 m/sec	29	28	26	19	6	4	3	4	9	16	19	28	16

*From U. S. Department of the Air Force, no date (a) and no date (b).

†Less than 0.5 day or percent.

Fig. 1—Monthly temperature data.

Fig. 2—Sky condition.

Fig. 3—Fog and precipitation frequency.

observed and the mean monthly precipitation (in millimeters and inches) are shown in Fig. 4. Data for the period October 1967 through June 1972 are given for comparison with mean monthly precipitation data for the 1940s. The mean annual total precipitation for February 1943 through June 1948 was 828 mm (32.6 in.); that for October 1967 through June 1972 was 953 mm (37.5 in.).

The 15% excess in mean annual precipitation of the later data over the earlier is not considered significant when one notes (from the later data) that the highest values in each month exceed the monthly means by values ranging from 20 to 107%.

SURFACE WINDS

The extreme variability of surface-wind directions at Amchitka is a result of the high incidence of migratory pressure systems. Figure 5 shows the seasonal paths of surface low-pressure centers. These storm tracks are based on data available from 1899 to 1954.

There is no prevailing wind direction as such at Amchitka, as shown by Fig. 6. There is little, if any, topographic channeling of the winds at the low end of the island where the data were taken. Summer winds tend to blow from the southwest quadrant because of the semipermanent high-

pressure area that persists in the Gulf of Alaska during the summer months.

Figure 7 shows the monthly mean wind speed and percentage frequency of hours with wind speeds equal to or greater than 14 and 21 m/sec [32 and 47 miles per hour (mph), respectively]. Wind speeds may exceed 45 m/sec (100 mph) in the Aleutians. In January 1969 the wind speed exceeded the 100-knot (51 m/sec, 115 mph) instrument scale at the Amchitka base camp.

CLIMATE OF B AND C SITES

In a climatological sense, the data for the airport [elevation, 67 m (220 ft)] are considered entirely applicable to the B site [40 m (131 ft)] and the C site [63 m (207 ft)] (see Fig. 11, Chap. 1).

We have observed that over the relatively low southeast part of the island there is no significant spatial variability in the large-scale wind direction and speed. True, eddies may be induced by small hills, gullies, etc., quite near the ground in the microscale circulations, but no instrumentation sufficient to define these microscale circulation patterns was ever used at Amchitka.

Fig. 4—Precipitation amounts and frequency of occurrence. ○—○, October 1967 through June 1972. ●—●, February 1943 through June 1948.

Fig. 5—Seasonal storm tracks, North Pacific Ocean (from Klein, 1957). Solid lines denote clearly defined (primary) tracks; broken lines denote less frequent or less well defined (secondary) tracks.

In a marine environment such as Amchitka's, one cannot conceive of significant temperature changes over such relatively short distances [B is 8 km (5 miles) and C is 16 km (10 miles) from the airport] or through a height change of only 4 to 27 m (13 to 89 ft), and, in the absence of pronounced terrain-feature differences, precipitation amounts or intensities would not be expected to vary beyond the limits of measurement accuracy.

Thus the long-term airport climatological data represent the best available data for the B and C sites.

CLIMATE OF THE HIGHLANDS

Climatological statistics presented here are applicable to the low southeast end of Amchitka for which long-term data are available. They only approximate conditions for the relatively mountainous areas of the island since most meteorological elements are affected by elevation, slope, and terrain shielding.

In general, one would expect the weather to be more severe in the highlands. Temperatures, in the absence of surface inversions, are usually lower

Fig. 6—Seasonal surface wind roses. The length of each direction bar represents the percent frequency of wind from that direction. Numbers at the end of each bar represent mean wind speed (meters per second/knots). The number in the center of the rose is the percent of calms.

with increasing altitude. Low clouds over the southeast end of the island would often be fog in the mountains. Moderate rain over flat terrain is often accompanied by heavier rain in nearby mountains, and, certainly, more snow accumulates and remains longer at high than at low elevations. The effect of elevation on temperature and the increase in wind speed caused by channeling over rugged terrain result in more severe storms in the mountains than in the lowlands.

SOLAR RADIATION

A pyranometer was installed at the airport control tower in February 1969 to obtain solar radiation data for the bioenvironmental programs. Fairly complete data were obtained from August 1969 through November 1971.

The pyranometer measures global solar radiation received on a horizontal surface. This includes both radiation received directly from the

Fig. 7—Surface-wind speeds.

solid angle of the sun's disk and radiation that has been scattered or diffusely reflected in traversing the atmosphere (sky radiation). The ratio of the sky radiation to the global solar radiation fluctuates markedly, from near unity when the sky is densely overcast to less than 0.1 under extremely clear conditions.

Figure 8 gives maximum, minimum, and average daily totals of solar radiation at Amchitka and, for purposes of comparison, the average daily totals for Seattle ($\sim 47.5^\circ\text{N}$) and Annette Island, Alaska ($\sim 55^\circ\text{N}$). The large differences between average daily totals for Amchitka and Seattle during the summer months may be accounted for by the fact that Seattle has a mean sky cover (sunrise to sunset) of about 50% (U. S. Department of Commerce, 1968) in summer, whereas fog predominates in the summer months at Amchitka.

The Amchitka data must be used only in a qualitative sense because of several uncertainties. Pyranometers in continuous operation require frequent inspection and cleaning (daily or oftener). There is no assurance that this was done since care of the pyranometers was by control-tower operators whose primary concern was certainly not

Fig. 8—Solar-radiation data.

accurate solar-radiation measurements. Frozen precipitation on the exposed envelope affects instrument accuracy, a factor that should be considered during the winter months. For these and other reasons, the data are not to be considered comparable with data from an observatory where particular emphasis is placed on obtaining solar-radiation data.

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Prehistoric Human Occupation of the Rat Islands

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Prehistoric Rat Islanders had an almost exclusively marine adaptation to their island group of 10 large to small islands. A large part of the Aleut population lived on Amchitka but interacted widely within the group for subsistence and social reasons.

Most previous archaeological investigations in the Rat group have been on Amchitka. Stress is placed in this chapter not on resulting artifact collections but on determinants of site location and how prehistoric Aleuts subsisted. Island size and shape, isolation, ecologic richness, and vulcanism are environmental variables thought to be important in differentiating one island from another. For any one island, such considerations as accessibility, exposure, resources, and defensibility make some coastal areas more suitable for village locations than others. Most Rat Island sites are relatively low sites with easy access to the sea.

Subsistence is organized into eight major procurement systems of hunting, fishing, and gathering on open seas,

littoral zones, or inland areas. These eight systems provided a stable subsistence pattern that, in turn, supported a large maritime population. Biotic variations between the Rat Islands suggest that Amchitka, Kiska, Rat, and Buldir were the most rewarding islands to exploit.

Because of their primitive technology and manner of building, prehistoric Aleuts had only limited long-range impact on the islands they occupied or on the fauna and flora they utilized. Their impact on the Rat Islands was indeed small when compared with that of modern man, especially World War II personnel.

Rat Island culture was similar to that developed in adjacent island groups. Conformity of artifact styles throughout the western Aleutians indicates the extensive social interaction that occurred among communities of this same area.

Modern man's impact on the western Aleutian Islands is all too obvious. Artifacts of our civilization are unavoidable to today's visitor. World War II roads, quonset huts, gun emplacements, recent Atomic Energy Commission (AEC) construction, and plastic trash accumulating on beaches from offshore fishing fleets all give evidence of man's intermittent presence.

Given the present scars on this fragile, subarctic biome, one might wonder about the counterparts deep in the area's prehistory. What debris and constructions did ancient Aleuts leave on the shores, and what were their collective effects on local ecosystems? We can provide only partial answers to these queries, and they are outlined here. This chapter summarizes what is known of human spatial factors, exploitation patterns, and cultural interaction. Our attention is focused on the reconstruction, incomplete as it is, of prehistoric Aleut participation in the prevalent marine ecosystem. Specifically, this participation is viewed within the Rat Island group, one of the major island clusters comprising the Aleutian archipelago. Thus this approach is simultaneously ecological and regional.

HUMAN ECOLOGY

Owing to the extensive environmental studies of Amchitka Island under AEC sponsorship, that island stands out as the best studied of any in the Aleutians. Scientists have accumulated much information about the island's physical environment and the biota inhabiting it and the surrounding seas. Because the majority of the biologic studies stress an ecological perspective, it is appropriate that man's participation also be summarized from the perspective of human interaction in various ecosystems.

Man adapts, as other organisms, by genetic and physiologic means, but man principally adapts through cultural mechanisms and therefore is unique among all life native to the islands. Such adaptive mechanisms are treated here to demonstrate how prehistoric Aleuts subsisted in the various ecosystems discussed in the other chapters of this book. It is subsistence that impinges most on the collateral Amchitka studies.

However, this summary describes not the totality of studied ecosystems but rather those in which man principally interacted. In delimiting man's

niche, we selectively integrate the relevant ecologic factors cutting across disparate ecosystems but characterizing man's existence. In this manner habitats and ecosystems treated by other investigators will be referred to only as they are exploited or affected by man.

This summary does not attempt to recreate all aspects of Aleut culture through archaeological or ethnohistorical approaches. For instance, we have no living Aleut population subsisting at a hunting and gathering level similar to that of the past. Therefore we cannot study ongoing Aleut energy flow as has been done among other contemporary hunters or farmers (Kemp, 1971; Rappaport, 1971) to discern past subsistence or ecologic interaction. At best, we can combine our archaeological and ethnohistorical data to suggest the general marine exploitation patterns followed by ancient Aleuts. Midden remains display direct evidence of subsistence, and therefore it is this broad area that we shall emphasize.

MARINE ADAPTATION

Today's visitor will note that the total native occupation of the western Aleutian Islands for several millennia left an insignificant physical record compared with modern occupations. Nevertheless, some alterations resulting from consistently occupying specific localities have had long-term effects. House construction and midden enrichment make these localities apparent today.* Most impact, however, was of a short-term nature, especially the impact relating to hunting and collecting, and demonstrates the close and direct interaction Aleuts had with various organisms and inorganic raw materials.

Besides interacting at a lower and less-intense technologic level than modern occupants have, prehistoric Aleuts interacted with a basically different aspect of the physical environment, the marine part, and less with the terrestrial part. The Aleuts had an almost total commitment to the sea. Land was a stable base of operations and retreat from foul weather, but, in subsistence terms, land was only important as it formed beaches that could be combed, lookouts for animal activity at sea, or natural concentration areas for marine mammals, birds, and fish.†

*Midden sites are pockmarked with house depressions; have lush dark-green vegetation stands dominated by *Heracleum lanatum*, *Angelica lucida*, *Ligusticum hultenii*, *Elymus arenarius mollis*, *Claytonia siberica*, and *Achillea borealis*; and have soils of high porosity, low temperature, and high organic matter, calcium, nitrate, and phosphorus (Bank, 1953). Figure 5 in Chap. 1 illustrates the manner in which midden sites stand out on the coastal landscape.

†For a discussion of island ecosystems and human adaptations to them, see Fosberg (1963).

Travel depended on large and small skin boats, the majority of food was secured from the ocean, and many raw materials were derived from sea-mammal exploitation. To the degree that Aleut technology via watercraft made essentially all the coastline accessible, the varied marine habitats along these shores were exploitable. Thus man, as the most flexible or generalized omnivore, was able to expand his dependence in more-varied habitats than any other Aleutian animal. At the same time, Aleuts essentially ignored many natural communities studied recently by ecologists because these could contribute few food resources. Exploitation of natural terrestrial communities was generally inversely proportional to their elevation above sea level and their distance from the shore.

Our ultimate measure of successful adaptation is found in the evidence of man's spread and the duration of his occupancy throughout not only this island group but also the entire archipelago. Aleuts lived on all large and most small islands and did so almost continuously for at least 2500 years in the west and 4000 years in the east.

AMCHITKA AND THE RAT ISLANDS

Amchitka has been the focal point of recent AEC-sponsored research, but, because man traveled widely in skin boats, prehistoric Aleuts cannot be adequately studied from one island locale. We may understand the characteristics of Amchitka's site distribution, population size, and subsistence patterns only in the regional framework of the entire Rat Island group.

The Rat Island group is clearly separated from adjacent island groups by Amchitka Pass on the east and the wide interisland passes surrounding Buldir Island to the west. This island group forms a natural spatial unit in which to operate, although Buldir is comparatively isolated and is included in the Rat group somewhat arbitrarily. Because danger from boating accidents is largely a function of water distance and turbulence, we may safely presume that early Aleuts also moved less frequently across these major passes than among the Rat Islands proper. Tides and currents between the Pacific Ocean and the Bering Sea in these passes today present the same boating problems faced by past kayakers. Within the Rat group, however, travel was relatively easy. On clear or semiclear days, other islands loomed large on the horizon (see island profiles on pp. 6 to 8 in Murie, 1959). In summary, water barriers around the Rat group created human behavioral boundaries that limited intergroup interaction.

Travel within the Rat group was not only possible but was required. Interisland travel, for

example, was a requisite part of subsistence exploitation. The Rat Islands are dissimilar in their food animal population sizes and in the presence or abundance of various rock and mineral resources serving as essential raw materials. A normal seasonal round would typically take an Aleut hunter, if not his family, to several islands in pursuit of foodstuffs and materials. Feasts or festivals often occurred between villages from different islands.

Volcanic eruptions in any of the group's several volcanoes likely caused a mass exodus to nearby islands for safety from raining ash. Attack from outside Aleuts also could have forced villagers to flee to another island for refuge.

Thus, to understand the relationship between Amchitka islanders or any other island population within the entire Rat Island sphere, we must approach the whole island group as an integrated series of ecosystems.

Finally, this chapter admittedly contains some necessary speculation owing to the incomplete archaeological record and our difficulty in interpreting that record. Precise delineation of settlement and ecologic factors is accordingly limited. Relatively few sites have been excavated in the Rat group, and a larger sample would permit interpretation and explanation at a higher level of confidence.

HISTORY OF ARCHAEOLOGICAL RESEARCH

Archaeological investigations of the Rat Islands span a period of a century. Dall (1877, pp. 47-48 and 51; 1878, p. 8) first excavated at Constantine Harbor, Amchitka (Site 3), in 1873. Hrdlička (1945, pp. 220-237 and 347-364) dug on Kiska and Little Kiska in 1936 and at Amchitka Sites 2 and 3 in 1938. World War II brought a large military population to the islands, which caused the most extensive damage to prehistoric sites since their initial occupation (Guggenheim, 1945). Summaries of archaeological investigations during and prior to 1945 in the western Aleutians are found in McCartney (1967, pp. 10-20), Turner (1970, pp. 118-119), Desautels et al. (1971, pp. 20-21), and Fuller (Chap. 7, this volume).

The interest of AEC in Amchitka as a testing ground renewed archaeological reconnaissance under the aegis of that agency. Fieldwork during 1968, 1969, and 1971 centered primarily on (1) inventorying all sites seen on the surface today,* (2) making test excavations in some of these sites, and (3) evaluating the effects of nuclear detonations on such sites. Results of the AEC-

sponsored research are presented in publications by Turner (1970), Desautels et al. (1971), Cook, Dixon, and Holmes (1972), and Merritt (1972). These results are summarized in the sections that follow.

Other recent archaeological research includes site surveys in the Rat group. Bank (n.d.) inventoried four sites on Rat Island and four on Kiska Island during the 1950s. McCartney (1972, pp. 25-26) surveyed 22% of the Rat group coast in 1972 by boat and added five possible sites on Little Sitkin, Khvostof, and Segula islands.

The only archaeological excavations and testing within the Rat group have occurred on Amchitka, Kiska, and Little Kiska. The coastlines of all the islands except Semisopochnoi have been surveyed for sites, but islands other than Amchitka have not been surveyed with equal rigor. Additional sites on these other islands will undoubtedly be found in the future.

1968 Reconnaissance

During 1968 Sense and Turner began with the Guggenheim (1945) site inventory of 40 known sites and expanded the total to 76. W. S. Laughlin, R. F. Black, and L. M. Gard also assisted Sense and Turner in their testing of 14 of the sites. Approximately 1400 stone and bone artifacts came from these tests, but their descriptions have not been published (Desautels et al., 1971, p. 21).

Turner (1970) briefly described test excavations at Sites 1, 2, 3, 13, 14, and 15 and human skeletons and fragments from Sites 3, 14, 15, 16, and 23. He estimated, on the basis of midden accumulation rate, that Amchitka sites dated to as long as 2500 years ago. This figure is substantiated by radiocarbon dates from lower levels of Sites 31 and 36 (range, 890 ± 90 to 2550 ± 95 B.P.; Desautels et al., 1971, p. 384). No sites as large as those known in the eastern Aleutians (e.g., Chaluka on Umnak) were noted.

The most important summation provided by Turner is that regarding determinants of site location. He notes that (1) site distribution is not random, most sites occurring in the southeastern half of the island; (2) sites typically were protected in embayments, were close to freshwater and food-rich intertidal habitats, had water approaches protected by kelp beds, and had easy access to the beach; and (3) no correlation was apparent between sites and driftwood sources or gross geologic formations. These site characteristics are explored at greater length in this chapter.

The 1968 collections have not, to date, been fully analyzed and published; they are now in the possession of the University of Alaska Museum

*Site locations on Amchitka are indicated in Fig. 1.

with the other AEC-sponsored collections. I have not personally inspected any of these collections.

1969 Excavations

The report of Desautels et al. (1971) is the primary descriptive document for Amchitka excavations and artifacts. Six sites (10, 14, 31, 35, 36, and 60) were tested during 1969, and 6800 artifacts were recovered from these tests. These six sites were chosen because they seemed most likely to be disturbed by nuclear detonations at the central and southeastern portions of Amchitka. Two additional sites (77 and 78) were added to the site inventory.* Six radiocarbon dates were determined, three each for Sites 31 and 36. Site 31 dates range between 600 BC and AD 1060 and come from a depth of 70 to 190 cm; Site 36 dates cluster between 295 and 105 BC, all being from 210 to 270 cm deep (Desautels et al., 1971, pp. 38, 48, and 384). The report fully presents the stratigraphy and features for the midden tests. Almost all the features are fire hearths (Sites 31, 35, and 36) or burials under wooden covers or within wooden sarcophagi (Sites 10 and 14) [similar burial features are described by Dall (1877, pp. 62-63; 1878, p. 8), Jochelson (1925, pp. 45-46), Weyer (1929), and Hrdlička (1945, pp. 179-180)]. Three skeletons, one adult male, one adult female, and one child, were found in Sites 10 and 14. No houses were uncovered.

The large artifact collections include 11 iron fragments, primarily of knife blades, and some of these, if not all, are of prehistoric age. These iron fragments are from Sites 14, 35, and 36. The

*Of the 78 sites thus far designated, 2 (Sites 20 and 21) are of historic age. Sites 24, 77, and 78 are designations for blowouts (areas of wind deflation) atop a high bluff at the center of the Bering Sea coast. Besides the fact that no midden debris or recognizable features were noted by Sense or Desautels at these blowouts, the "artifacts" alone are questionable. Because there are essentially no recognizable Aleut artifact forms among the illustrated examples (Desautels et al., 1971, pp. 376-383) which relate to the other midden sites, we must assume that, if these are, in fact, human occupation sites, they are much earlier than the middens that are as much as 2500 years old. If we assume that these pieces represent a prior and heretofore unrecognized Aleutian culture, they should show some relationship to the only early human assemblage in the chain, the Anangula core and blade industry off Umnak (McCartney and Turner, 1966). However, no prismatic blades, polyhedral cores, transverse burins, and related tools were found at Sites 24, 77, and 78. Some cobble hammerstones are individually similar to recent specimens. But, taken as a tool complex, these pieces are not recognizable as a human tool assemblage. They are quite likely naturally fractured rock fragments (eoliths) and must be held in abeyance until further proof of their human origin is offered. Excluding these 5 sites, the Amchitka site total described here is 73.

artifact analysis is a formal, hierarchic classification of descriptive categories including four levels. No major stylistic or cultural changes were noted by the excavators in any midden sequences. A late artifact complex was suggested for the period AD 1000 historic contact. This complex includes nine classes or general techniques from specific kinds of bone needles to "new styles of bone ornamentation."

A faunal analysis of Site 31 debris indicates that the bone sample breaks down into approximately 85% fish, 10% sea mammal, and 5% bird bones by weight. Of the sea mammals, 59% are sea otter, 33% are harbor seal, 6% are sea lion, and 2% are fur seal by bone count (Desautels et al., 1971, pp. 314-340 and 359-367). Whale bones are also found in low unspecified frequency (Desautels et al., 1971, pp. 38-39). Sea urchins comprise over 90% of the marine invertebrate remains. This analysis is consistent with the midden matrixes of other eastern and western island groups.

1971 Excavations

Additional site excavations were made in 1971 at Site 32 in the middle of the Pacific Ocean side of Amchitka (Cook, Dixon, and Holmes, 1972). This site was considered to be endangered by the projected 1971 Cannikin detonation. The major contribution of this work was the excavation of a complete house dating to about AD 1500. Four radiocarbon estimates date the Site 32 midden between AD 85 and 1750. A total of 546 artifacts were recovered in the 1971 tests.

Of a total of seven possible houses noted at the site, only one was completely excavated. This house is the only fully uncovered house yet described in detail in the chain. Another house or two have been fully excavated at Chaluka midden, Umnak, but no details have been published. Previous tests at other Amchitkan sites have uncovered only portions of house features. The Site 32 house measures 7.5 by 6.0 m in outside dimensions, was built directly on bedrock, and was built almost entirely of driftwood rather than whale bones. Because of the rock base, which prevented drainage, the structural members of the house have been preserved by groundwater saturation since the house collapsed. The Aleutian pattern of covering house roofs with sod made it possible for the wet sod to seal in and protect the wooden wall and roof pieces from wind dispersal or weathering.

The site reports by Desautels et al. (1971) and Cook, Dixon, and Holmes (1972) are important contributions to western Aleutian archaeology. Only Jochelson (1925, pp. 24-26) and Spaulding (1962) report on systematic site excavations in the

Near Islands to the west. Hrdlička's (1945) excavations on Amchitka, Kiska, and Little Kiska were never properly documented. No archaeological reports are available from the adjacent Andreanof group to the east except Jochelson's (1925, pp. 26-29) short section on Atka excavations.

Although the two recent Amchitka reports shy away from cultural comparisons and syntheses of the Amchitka collections within the extant literature on Aleutian and southwestern Alaskan archaeology, they do provide us with accurate and specific archaeological information for these broader cultural comparisons.

Detonation Effects

Merritt (1972) provides a short summary of the effects that the three nuclear detonations [Long Shot (1965), Milrow (1969), and Cannikin (1971)] had on archaeological sites. Such sites are particularly vulnerable because they often rest at the unstable edges of coastal marine terraces that are slowly eroding. Ground shocks can easily cause rock falls and mass wasting at the island's periphery.

No documented damage to sites resulted from Long Shot, probably because of its low yield. Milrow caused rock and turf slides on both the Pacific Ocean and the Bering Sea coasts. Some 1968 excavation profiles caved in as a result of that test. Cannikin caused the coastal bluff at Site 32 to slump, destroying approximately 5% of the site. The excavation profiles at Site 32 also slumped from the ground-wave shock. Of 10 other sites near the test point, only 1 (Site 67) showed evidence of shock damage.

It is too early to observe possible long-term effects of the three nuclear detonations on the island's margins. Undoubtedly the resulting ground-wave shocks are responsible for putting additional cleavage cracks through sites resting on unstable terraces. Such disturbances could likely go undetected beneath the thick surface vegetation. However, no comparative, long-term records of site and coastal slumping are available from other islands, and therefore it is unlikely that damage from shock effects will be measurable in the future.

If any Aleutian Island had to be chosen as a test site, we recognize with hindsight that Amchitka was a fortunate choice. Amchitka has a greater-than-average number of prehistoric sites representing a large aboriginal population. Thus archaeologists now have a newly inventoried site series available with which to plan further research. The artifact samples and excavation details thus far

collected from a few of these sites will serve as an important nucleus for future cultural analyses.

SITE CHARACTERISTICS AND DISTRIBUTION: THE HUMAN SPATIAL DIMENSIONS

As a natural geographic unit, the Rat Islands* constitute an archipelago of 10 large to small islands totaling approximately 1000 km². These islands are distributed irregularly as exposures of the Aleutian ridge between the Andreanof and Near Island groups. The islands vary horizontally between rounded, linear, or irregular shapes and vertically from low to high. The highest point on Little Kiska is less than 61 m (200 ft) in elevation, whereas peaks on Kiska, Segula, Little Sitkin, and Semisopochnoi reach about 1220 m (4000 ft).

Numbers and Kinds of Archaeological Sites

To date, 86 definite prehistoric sites plus five possible sites have been located in the Rat group (McCartney, 1972, pp. 25-26). The possible sites were noted during a 1972 U.S. Fish and Wildlife Service survey of the Rat Islands but have not been confirmed by shore inspection.

The majority of the sites (73) are found on Amchitka or on offshore islets around Amchitka (Desautels et al., 1971, p. 23). This Amchitka total excludes 2 historic sites (20 and 21) and 3 sites of dubious authenticity (24, 77, and 78) from an original total of 78. These 92 site locations are shown in Fig. 1.

Most of this section treats the Amchitka sites, although comparative notes on other Rat Islands are included. The emphasis on Amchitka derives from the intensive site surveys of that island over the past five years. Amchitka is the only major island of the Rat group on which all large midden sites appear to have been discovered. Therefore this island provides a unique opportunity for the study of site locations in the western chain. An occasional camp site may be added in the future, but it will not significantly alter our generalizations about site distribution. The only large island in the eastern chain to be completely surveyed for sites recently is Akun (Turner, 1973).

*The Rat group islands are here considered to number 10, including Buldir. These are all islands measuring more than 1.6 km (1 mile) long. Several islets smaller than 1.6 km in maximum dimension include Bird Rock off Amchitka and Pyramid Island between Davidof and Khvostof. Three islets off Amchitka's shore, including Bird Rock, have one or more sites, but these are tallied with Amchitka proper. Buldir is the most isolated island, about halfway between the Rat and the Near Islands, but it is considered to be one of the Rat group (Orth, 1967, p. 166).

Fig. 1—Maps of the Rat Islands showing known archaeological sites (dots). Known site totals are given in parentheses. Islands less than 1 mile (1.6 km) long are not included.

Although we have close to 100% of all Amchitka sites to analyze, we know little about how each functioned or differed from others. We must presume that large midden areas represent stable villages that were occupied for most, if not all, of the year. Small sites are presumed to have been seasonal camps, such as fishing stations, but sites do not aggregate into clearly separable types on the basis of size, depth, elevation above the beach, sampled artifact content, or other obvious characteristics. Therefore this section is devoted to a review of spatial variables or determinants in an attempt to better understand why Aleuts established sites where they did.

Three related factors restrict our current knowledge of site function. Most sites have never been systematically excavated for archaeological data that would bear on the question of function, seasonality, and duration of occupation. Second, the World War II military occupation is estimated to have damaged 60% of Amchitka's sites (Desautels et al., 1971, p. 2), leaving, in some cases, no undisturbed strata to be tested today. Third, the 1968 artifact samples from 14 different sites have gone unpublished. Specific information about intersite variation that might have come from such an analysis is therefore not available.

Because we cannot ascertain specifically how past Aleuts moved from base settlements to seasonal camps during the yearly subsistence round, we must consider each site a cultural entity by itself, representing a distinctive social/political group over an unspecified period. Yet, in at least seven instances on Amchitka, two sites are located very close together (<0.5 km or 0.3 mile). If these were occupied contemporaneously, these double sites may have been different occupation areas for the same people. Six of these double-area sites (2-3, 6-43, 22-23, 31-56, 32 high and low, and 35-36) comprise a high area and a low area essentially side by side. It is possible that the different elevation areas represent a seasonal shift up and down a common slope (Desautels et al., 1971, p. 347). The seventh site pair (72-73) is an example of two high sites.

Because the distance separating any site pair is so slight, it appears unlikely that the sites represent simultaneous but discrete political/social groups. As an alternative, however, these site pairs may have been occupied sequentially, with a later village or camp being established in proximity to, but not directly on, a former settlement.

Since we lack precise cross dating between any of these site pairs or analytical tools for discerning if the same group occupied two slightly separated areas, we assume here that each individual area

represents a different settlement at different periods of time.

The following summary excludes those site-location determinants related to the Aleut spiritual world or those which have no clear ecological significance. While stressing a kind of mechanistic approach to man's use of the physical and biological environment, we recognize that other cultural pressures exist for establishing communities, moving about, and exploiting certain ecosystems. A village may have been consistently occupied in part because strong ties to ancestors or spirits residing there dictate such a behavior. One food resource may have been overlooked in lieu of another because of taste preferences. Motivation for moving an encampment may have sprung from desires to "keep moving" rather than depletion of the local food supply.

In short, man has many complex inducements guiding behavior, and we should not minimize nonecological cultural pressures when viewing man interacting in the Aleutian environment. But, because we have little knowledge of nonecological factors, the determinants described here portray man interacting with spatial and ecological limitations.

Interisland Determinants

Of first interest in inspecting the Rat group sites is why 80% of them fall on Amchitka. The fact that Amchitka is a relatively large island is insufficient to explain the site concentration. A partial explanation is that site surveying has not taken place as intensively on the other islands as it has recently on Amchitka. But a more critical factor appears to be operating; i.e., the other islands are not as suitable for human occupation.

On probing into differential site suitability and irregular site distribution of past Aleuts, we find several overriding patterns. First, different islands were not occupied with equal intensity. Second, on the same island site distribution was never uniform along the coast, and sites were never located in the interior. Third, on the coast only lower benches and terraces were commonly occupied. Finally, even in these lower coastal zones, still other considerations apparently influenced the location of a habitation site.

In this section some of the key determinants that help explain the utilization of the land mass for seasonal or year-round settlements are examined. Variation between islands is treated first, followed by variation around the same island.

Future field observations and excavations should be directed at testing these determinants as hypotheses. Enough evidence is available to suggest

strong positive associations between site localities and these variables, but greater analytical precision and model testing may permit us to derive causal explanations for the phenomena observed.

Island Size and Shape. Depending on its size and shape, one island may provide greater or lesser coastal living space to prehistoric inhabitants than another island. Perimeter is a function of size, but it also increases with the degree of deviation away from circular plans and/or smooth coasts. A narrow island or one with convoluted and indented margins will have a greater perimeter than a round island or one with unindented coasts. As a measure of the relationship between area and coastal length, a ratio or *index of irregularity* is calculated for each of the Rat Islands to show their degree of deviation from circular, regular coastlines (Table 1). Because area and linear measures are not proportional, this index is necessary to compare islands of differing shape and shoreline indentation regardless of island size. This table clearly shows that Amchitka (298.4 km²), Kiska (296.6 km²), and Semisopchnoi (238.6 km²) are the largest

islands, but Semisopchnoi is distinguished from the former two by having a lower index figure (4.69). Semisopchnoi's circular shape, relatively regular coast, and comparatively small perimeter confirm this low index. Besides Amchitka and Kiska, Rat Island also has a larger index (7.02) than most, indicating that it falls between Amchitka and Kiska on the one hand and the rounder islands (3.94 to 5.07) on the other. Although Rat has less area (30.3 km²) than Segula (36.5 km²), it has a larger index because of the longer coast.

In terms of human occupation, island area alone is not so important as perimeter or index of irregularity. Only the coast or periphery is utilized for subsistence, and therefore island perimeter is a more meaningful figure than area. The greater the coast length per unit of area, the larger the potential population that could be supported by resources along it.

Given the limited size range of Aleutian Islands, the index figures make it possible to compare the likelihood of travel across any island if elevation and terrain are disregarded. Distances across islands will be less on islands with higher indexes. Although sites are not found inland, away from the coast, the ability to traverse an island's interior may have been crucial when considering escape from attackers arriving by boat or exploitation of additional coastal zones. However, elevation and topography are important in determining the ease with which Aleuts might cross from one side to another. Vertical shape, therefore, may be rather important under certain cultural conditions.

Most of the Rat Islands are volcanic cones (Buldir and Segula), calderas (Little Sitkin and Semisopchnoi), or caldera remnants (Davidof and Khvostof) (Coats, 1950, pp. 38 and 43). Kiska has a volcanic cone on the northeastern end. Amchitka, Little Kiska, and Rat have no active volcanoes or resulting cones. All the islands are mountainous except for southeastern Amchitka, northwestern Rat, and Little Kiska, which have low marine terraces or platforms of less than 91-m (300-ft) elevation. Thus island crossings were relatively easy over the last three islands but were rigorous over the former seven islands.

Isolation. The Rat Islands are irregularly scattered along this part of the archipelago (Fig. 1). We would expect the most isolated island or islands to support the least population insofar as isolation should be inversely related to group safety in attacks and to food sharing and other social interaction during periods of stress. Occupying part of an island nucleus or cluster would therefore be of advantage, in contrast to occupying an island

Table 1—Rat Island Area and Perimeter Measures

Island	Area,* km ²	Perimeter,† km	Index of irregularity‡
Amchitka	298.4	194.7	11.27
Kiska	296.6	160.9	9.35
Rat	30.3	38.6	7.02
Little Kiska	8.8	17.7	5.96
Davidof	4.7	12.9	5.94
Segula	36.5	30.6	5.07
Khvostof	2.6	8.0	5.00
Little Sitkin	68.8	39.4	4.75
Semisopchnoi	238.6	72.4	4.69
Buldir	20.2	17.7	3.94

*Calculated from USGS 1 : 250,000 maps; approximate accuracy, ±3%.

†Calculated from the following: Little Sitkin, 1 : 20,000 map; Davidof, Khvostof, Segula, and Semisopchnoi, 1 : 25,000 map; Kiska, Little Kiska, and Rat, 1 : 63,360 maps; Amchitka, approximately 1 : 103,000 map; Buldir, 1 : 250,000 USGS map; Buldir perimeter is the least accurate owing to the small scale of the map used.

‡Index of irregularity [perimeter/(area)^{1/2}] is a measure of overall shape, including coastline indentations; coastline indentations cannot be meaningfully partitioned from overall island configuration. However, it is the general configuration of the land mass comprising the island, and not coastal irregularities, which influences the resulting index the most. For comparison, a circle has the most economic ratio of coastline to area (3.55); Amchitka has one of the highest for all the Aleutians (11.27). Almost all other islands will fall between these extremes. These indexes can only be interpreted in an ordinal manner, and their value is in judging relative shape deviations among islands.

frontier where no nearby island could afford safety.

Table 2 shows the minimal distances between islands. It is clear that Semisopochnoi and Buldir, respectively, on the east and west ends of the island group, are the most isolated. The remainder form a central core or island network in which the maximum distance traveled to participate would be 27.4 km.

Table 2—Interisland Distances

Island	Minimum distance to next closest island,* km
Buldir	117.5 (to Kiska)
Semisopochnoi	53.9 (to Amchitka)
Kiska (and Little Kiska)	27.4 (to Segula)
Amchitka	21.7 (to Rat)
Rat	13.7 (to Davidof)
Segula	5.6 (to Khvostof)
Little Sitkin	5.6 (to Davidof)
Davidof	1.6 (to Khvostof)
Khvostof	1.6 (to Davidof)

*Map reference, USGS 1 : 250,000.

As a correlate of isolation, direct visibility between Kiska and Buldir is lacking at sea level. To see Buldir's almost 671-m (2200-ft) peak from sea level as a kayaker would, the boater would have to be within at least 104.6 km of Buldir (U.S. Coast Pilot 9, 1955, endpapers). Since the actual distance between Kiska and Buldir is 117.5 km, a boater would have to be at least 12.9 km west of Kiska to glimpse Buldir on the horizon. However, Buldir could be seen from a higher vantage point on Kiska. The remaining islands, excluding Rat, Khvostof, and Davidof, would be mutually visible to boaters offshore any island. Murie (1959, pp. 6-8) demonstrates the between-island views of this central-island core. Of course, Aleutian weather is rarely clear enough to afford good visibility over the longer interisland distances.

Although we are only considering one variable here, isolation, note that Buldir and Semisopochnoi have but one reported site each.* Buldir has been closely surveyed on foot, but Semisopochnoi probably possesses a few more sites. If not the only causal factor, isolation at least appears to be positively associated with low population density.

Ecology. Past Aleuts surely distinguished one island from another on the basis of subsistence

abundance. Yet such distinctions are impossible to reconstruct directly thousands of years later. All the larger Rat Islands offer varied shorelines that are habitats for marine mammals, fish, invertebrates, birds, and algae. Thus these islands seem to provide a suitable ecologic situation for prehistoric Aleut occupancy.

One meaningful measure of relative richness may be shallow waters around island peripheries. Pinnipeds, sea otter, inshore fish, kelp, and invertebrates occupy shallow coastal waters where they could be used by Aleuts. Estimates of shallow coastal waters are given in Table 3. Shallow waters are here arbitrarily defined as <30 fathoms; the 30-fathom contour marks the maximum sea otter feeding depth (Kenyon, 1969, pp. 66-69).

By calculating a ratio of area to circumference, we see that Rat Island has more shallow coastal water per shore kilometer than any of the other islands. Little Sitkin, Davidof, Khvostof, and Segula have the least. We might expect a greater relative abundance of food and material resources to be found off Rat, Buldir, Amchitka, and Kiska. But, in absolute figures, there is greater area found around Semisopochnoi (80 km²) than around Buldir (32 km²).

Because no one island stands out as being totally depauperate of Aleut food staples, the key consideration is not if but *how much* Aleut subsistence could be supported on any particular island.

Table 3—Estimated Shallow Coastal Waters for the Rat Islands

Island	Coastal area with water depth <30 fathoms,* km ²	Island perimeter,† km	Ratio of area to perimeter
Rat	88	38.6	2.28
Buldir	32	17.7	1.81
Amchitka	329	194.7	1.69
Kiska and Little Kiska	228	178.6	1.28
Semisopochnoi	80	72.4	1.10
Little Sitkin	36	39.4	0.91
Davidof and Khvostof	17	20.9	0.81
Segula	22	30.6	0.72

*Coastal areas are calculated from USCGS 1 : 300,000 map (No. 8864, 1965). Because the submarine ridge connecting Rat and Kiska is less than 30 fathoms, the 30-fathom area around these islands is arbitrary at one end of each island. The only check on these figures is an Amchitka estimate of 376 km² (110 sq nautical miles; Kenyon, 1969, p. 150) within the 30-fathom contour. The earlier estimate may be more accurate in absolute terms, but the area estimates in this table are accurate relative to one another since they are all made on the same map.

†Perimeter estimates are from Table 1.

*The single Buldir site is a small one found by Jones (1963, p. 84). The Semisopochnoi site was reported in 1971 by T. R. Merrell (written communication, 1975).

The ecologic factor was critical to Aleuts but unfortunately eludes us now. There is danger in assuming that site density on an island is a direct indicator of ecologic richness and diversity; some islands may have offered poor village locations yet may have been intensively exploited by transient marine hunters and gatherers from nearby islands. In the exploitation section below, modern animal population estimates are given as one indicator of differential island resources.

Vulcanism. Volcanic eruptions can, at the least, destroy food resources for several months and cause dire psychological trauma to local inhabitants. Three Rat Islands, Kiska, Little Sitkin, and Semisopochnoi, have volcanoes that were active during the historic period (Coats, 1950, p. 38, Table 2). Other volcanoes occur on Buldir and Segula. All these may have erupted occasionally during man's 2500+ year occupancy of the Rat group. Aleuts living on these islands or on islands downwind would be especially affected by ashfalls. The volcanic cone islands are arranged in an east-west line from Semisopochnoi to Buldir. The dominant upper-air winds are toward the east and northeast, and therefore ashfall effects were probably minimal on Rat and Amchitka, which are located to the south of the volcano line. Effects of ash fallout on flora and fauna are outlined by Wilcox (1959), Malde (1964), and Elliott (1886, p. 161).

Intraisland Determinants

The following factors are thought to be important determinants of where habitation sites will occur on the coast of any particular island. They are usually interrelated but are discussed here as independent variables.

Accessibility. Aleuts as maritime travelers could encircle and utilize essentially the entire edge of an island in a skin boat, weather and water conditions permitting. However, shoreline use adds the vertical dimension that restricts movement more than does the water surface. Three related factors are critical in occupying a shore as a village area or regularly for any other purpose: (1) beach configuration, (2) height of living space above the beach, and (3) slope angle between the beach and the living space. We are concerned here only with the attitude of land meeting the water in the vertical plane; horizontal shoreline configurations are treated in the next section.

At one extreme we find gently sloping, sandy or cobble beaches with storm benches above them. Such driftwood-strewn beaches give easy access to higher marine terraces or other level plateaus only

a short vertical distance above the active beach. Such a situation would be perceived as an easy landing locale not only by ourselves but also by past Aleuts; sites are likely to be found in such beach areas. At the other extreme we readily find sections of shoreline that are sheer rock cliffs rising out of the water in an almost perpendicular manner to a height of over 50 m. Obviously, no landing is possible at this kind of shore, and no villages will be located where such conditions exist. Between these extremes are located most of the Rat Island and other Aleutian sites.

Six major shore-profile types are presented graphically in Figs. 2 and 3. These types illustrate the variables of accessibility. Some of the shore profiles shown are from the Rat Islands and others are from the eastern islands. These profiles include all the major shore forms for the entire island chain.

Almost all settlements are found on Type 1, 2, or 3 shores. These have the minimum requirements of a beach for landing skin boats, a roughly level to gently sloping plateau or tableland into which houses were excavated and where village activities occurred, and a short vertical distance between the beach and the living area. Of course, shortcomings in one or two of these requirements may be offset by others if they make the site especially amenable to human occupation. The upper limit of Amchitka house sites appears to be about 30 m above high tide except for Site 75 (68 m, see discussion below).

Types 4, 5, and 6 shores are inaccessible because there is no beach to land on, a sheer cliff to scale, or no level living area short of climbing hundreds of meters up a steep incline if then. In other words these shores cannot be occupied with ease.

Any one island may evidence all six shore profiles illustrated at one or more spots along its coast or it may be fairly uniform in shore type. Volcanic cone islands, like Semisopochnoi, Segula, or Buldir, are rather uniform in steep, constructional shores. Amchitka is generally uniform in the Type 3 manner. However, islands such as Kiska or Rat show great variety in their shore configurations. As will be demonstrated later, these shore profiles become important when one tries to determine where man might have lived on these coasts and therefore how many people might have optimally occupied an island. In other words much of an island's shore may be safely excluded from the search for habitation sites because such areas are virtually impossible to occupy from the sea surface. Burial and other special sites may indeed be found atop high steep coasts, and searches for such nonhabitation sites should be conducted.

Fig. 2—Types of Aleutian shore profiles on which archaeological sites occur. Types 1 to 3 are low coasts with landing edges and flat living spaces above.

A survey of the 10 Rat Islands shows that only part of any island's shore is relatively low in the manner of Types 1, 2, or 3. Table 4 summarizes these low coastal zones. The table illustrates that, although suitable low coasts vary between 0% for Davidof and Khvostof and 59.5% for Amchitka, percentages cluster at 5 to 24% and at 38 to 60%. Except for Amchitka and Rat, the average low coast for the 6 remaining islands is 13.7%. Therefore, taking accessibility as a major prerequisite for site suitability, we find only a small part of most islands suitable for village or camp localities.

When low-coast percentages are compared with actual known site distribution (Fig. 1), the sites almost always fall along low coasts. The majority (82%) of Amchitka sites are found on the southeastern 60% of that island, which is lower than the northwestern end. Coastal cliffs are higher on the northwest, except at the extreme tip, and inland terrain ranges between 183 and 366 m (600 to 1200 ft); southeastern terrain ranges between 30.5 and 91.5 m (100 to 300 ft). On other islands sites are almost invariably found at mouths of stream-eroded valleys as they front on the sea or on low

Fig. 3—Types of Aleutian shore profiles on which archaeological sites do not occur. Types 4 to 6 are too high and/or too steep for human occupation.

terraces. Again we must remember that intensive site surveys comparable to those on Amchitka have not been conducted on the other Rat Islands, but recent surveying and records of previous investigators (McCartney, 1972) all corroborate the low coast—prehistoric site association.

In speculating about the total number of prehistoric sites in the Rat Islands, we use Amchitka as our referent because we know the locations of essentially all the sites ($N = 73$). If we compare numbers of sites to low coast, we find a ratio of about 0.63 site per low-coast kilometer.

Using this ratio and disregarding other island determinants outlined above, we may project a total of 110 sites for the Rat Islands. We already have 73 for Amchitka plus 19 found on seven other islands. We might expect to find about 18 additional sites on islands other than Amchitka in the future. If accessibility is, in fact, shown to be the most critical factor in site location, then this postulated total capacity for sites would be approximately accurate. If we assume a 110-site total for all the Rat Islands, Amchitka will have about 66% of these sites. Amchitka, Kiska, and Rat, the

Table 4—Low Coast Distribution on Rat Islands

Island	Perimeter,* km	Low coast suitable for sites,† km	Percentage of total perimeter	Major low coast areas
Amchitka	194.7	115.8	59.5	SE 60% of the island.
Rat	38.6	14.5	37.6	SE end near Ayugadak Pt.; NW 30% of the island.
Segula	30.6	7.2	23.5	S coast; NW coast between Zapad Head and Gula Pt.
Little Kiska	17.7	3.2	18.1	W end of the island.
Kiska	160.9	23.3	14.5	Kiska Harbor on the E; W coast between Witchcraft Pt. and Vulcan Pt.
Semisopochnoi	72.4	8.0	11.0	Alluvial valleys on E and W bays.
Little Sitkin	39.4	4.0	10.2	Williwaw Cove on the N; Sealy or Prokhoda Pt. on the SE.
Buldir	17.7	0.8	4.5	NW alluvial valley.
Davidof	12.9	0	0	
Khvostof	8.0	0	0	

*See Table 1 for map source.

†These approximate figures are estimated from the same map sources as in the preceding footnote; low coasts are here taken to be coastal zones of <30 m elevation, comprising flat marine terraces, alluvial terraces, or sloping sand and cobble beaches. Only general coastal areas are measured; a small, isolated spot may be suitable for a village but may not be detected on the maps used for checking these coasts.

three islands with the maximum low coasts, will have about 87% of all Rat Island sites.

Recent AEC study of Amchitka has made that island our best reference base for site distribution. Additional site surveys on other Rat Islands may test this coast-site relationship for the entire group. By checking and adjusting the regularity of this relationship within the Rat group, one may find such a ratio to be of great value in testing site-population capacities in other parts of the chain.

We have referred (Table 4) to low coasts being limited to approximately 30 m above sea level. There is no clear division at this elevation, but most Amchitka sites appear to have this elevation as an upper limit. Desautels et al. (1971, p. 22) note that sites fall into two general classes on Amchitka, high bluff sites and low beach terrace sites. Site elevations are shown in Fig. 4. There are discrepancies in height and size estimates between Desautels et al. (1971) and preliminary survey records of 1968 (Sense and Turner, 1970). Figure 4 treats the preliminary survey elevation estimates; precise site measurements will probably alter these figures slightly.

The elevation distribution shows a break at 13 m, those below referred to as low sites and those above as high sites [low coasts (<30 m) are not to be confused with low sites (<13 m) as discussed in the text]. Slightly over half of these total sites are low sites. Almost all the sites at 8.9 m or less are found on or behind beach storm terraces; half the sites between 9 and 12.9 m are on beach terraces and half are on low bluffs.

Fig. 4—Histogram of Amchitka site elevation frequencies based primarily on 1968 site survey forms. Measured from approximate high-tide line.

The high bluff sites fall predominantly at three elevation levels, 15.3, 22.9, and 30.5 m, reflecting the natural elevation of different parts of the island's periphery, or possibly reflecting the general use of rounded elevation estimates in units of 50, 75, and 100 ft, respectively. There appears to be less of a height continuum for high sites, but

precise measurements of elevation may show more variation than is reflected in these figures.

The highest site (Site 75; 68 m) is found on Windy Island off the Pacific coast of Amchitka. The site is atop a hill on this islet which falls directly to the low beach below. The elevation alternatives for a camp are therefore severely limited.

Exposure. Site exposure may be measured roughly in terms of protection offered from wind and other weather elements as well as by aspect, i.e., direction faced in relation to the trend of the seacoast.

Settlements theoretically could be established (1) on straight regular coast, (2) on headlands and points, or (3) on embayments. Although we find all three situations in the Rat Islands, the large majority of Amchitka sites is found in concave embayments (see Fig. 1). By settling in bays, bights, or coves, Aleuts found protection from the ever-present wind along beaches isolated between headlands. Bay shores are almost universally lower than headland shores on either side because headlands are formed by steep, resistant rock exposures while bayhead shores are formed by alluvium and beach deposition. Thus bayhead shores are typically Type 1 profiles, and headland shores are typically Type 5 or 6 profiles.

Beaching a skin boat would be simpler in the quiet waters of such embayments, especially if an exposed reef or kelp beds prevented breakers from entering the beach area. Reefs 30 to 90 m wide are almost always found before Amchitka's sites, and kelp beds almost totally surround the island. Operating from the head of a bay, a villager would survey a curving shore that could be exploited easier than a straight or convex coast since he could travel by skin boat across the water at chords to the curved shore.

The index of irregularity described earlier will suggest the degree to which one island is likely to have greater or lesser local protection for shore use. The higher the index, the greater the probability that there will be numerous coves and embayments offering protection from the wind and weather.

The ethnohistoric literature is confusing about the relation between site location and coast configuration. Veniaminof (1840, Vol. II, p. 200) states that villages (age unspecified) are "laid out. . . for the most part, in bays and gulfs in order to have as convenient a landing station as possible." Jochelson (1925, p. 23), however, states that "ancient Aleut villages" were normally located "on narrow isthmuses, on necks of land between two ridges, on promontories, or narrow sandbanks." Although it is true that such localities

often have old sites, isthmuses, necks, and spits are relatively rare on any Aleutian island. The Amchitka site distribution substantiates Veniaminof's observation that protected embayments are where sites were usually located.

Another variable of site exposure is aspect, or direction faced in relation to the sea. Aspect and its relation to wind and storm directions during the seasons the site was occupied would be important insofar as it influenced the ability to survey the sea surface and easily encounter sea mammals. Figure 5 is a directional rose indicating percentage directions toward which Amchitka sites face. Site

Fig. 5—Directional rose showing frequencies of the way Amchitka archaeological sites face the open sea.

facing is defined as the direction perpendicular to the shore immediately adjacent to the site looking outward from the site.

The two major directions faced, southwest and northeast, are perpendicular to the long axis of the island. However, more sites face south than north, making the orientation toward S-SW slightly predominant over that toward N-NE. If we tally sites on the two long sides of Amchitka, we find 31 or 44% facing the Bering Sea and 40 or 50% facing the Pacific Ocean. Two other sites face the northwest at that end of the island. There is no significant association between ocean frontage and site elevation; of 39 Pacific Ocean sites with elevation data, 20 or 51% are low and 19 or 49% are high. Bering Sea and Pacific Ocean site frequencies correspond closely to present-day sea otter distribution (Bering Sea, 40%; Pacific Ocean, 60%) (Estes and Smith, 1973, p. 65). Whether

distributions of sites and sea otter are meaningfully associated, however, is impossible to determine on current evidence.

The relative proportion of sites on the Pacific Ocean and the Bering Sea is of interest because Veniaminof (1840, Vol. II, p. 200) states that during the early nineteenth century "the greater number of villages" faced the Bering Sea. Sarichev (1807, p. 72) earlier reported that Fox Island settlements were not located on the southern or Pacific Ocean coasts. Amchitka sites, at least, do not corroborate these conclusions for the prehistoric period.

Resources. Resources (food, water, and raw materials) are grouped here as a major determinant of site establishment. Yet resources and defense, described next, appear to be more problematic as determinants than those already discussed. Behavior patterns surrounding resource use and defense are understood only indirectly. We can only roughly assess past resource abundance at any particular coastal area on the basis of modern abundance. Likewise, the efficiency with which Aleuts may have procured such resources can only be assumed.

Resource availability and original population size should be directly related. Large villages require abundant resources for support. We have some direct evidence of resource utilization from the archaeological site record, but exactly how a particular resource was used is not clear in all cases.

Beginning with food, we may presume that some coastal areas were favored variously for their sea lion rookeries, seal hauling grounds, sea otter-kelp beds, urchin and shellfish habitats, fishing spots, bird rookeries, plant collecting zones, etc. Yet how important these specific resource areas were to people choosing a site locality is difficult to evaluate because we have almost no historic-period settlement data for comparison.

Aleuts probably avoided living immediately adjacent to sea mammal or bird rookeries to avoid disturbing these animals. To choose a site just for its access to marine invertebrates or summer plants would seem unlikely, although these food organisms were usually available (Veniaminof, 1840, Vol. II, p. 200). Access to a major resource like whales could not be facilitated except in a gross manner as in choosing a site overlooking an interisland pass where cetaceans commonly travel. Since the Aleuts were quite mobile in skin boats for almost all the year, we must not consider them bound to specific areas for resources. Hunting and fishing from boats required extensive travel, often around or out from more than one island.

Further, any shifts in submarine and terrestrial habitats may have caused corresponding shifts in animal occupation of such habitats over several millennia of human occupation. We cannot assume that present habitats have gone totally unchanged over time.

Freshwater close to a site, preferably in the form of a stream, was desired (Veniaminof, 1840, Vol. II, p. 201). Certainly a number of Amchitka sites typically have streams adjacent or close to them. Living by streams may also be important because of salmon spawning in some of them during the summer, thus concentrating a valuable food resource. However, drinking water from streams is not considered to be critical owing to the wet climate and abundant springs and seeps that are almost ubiquitous to the Type 1 and 3 shores.

Nonfood material resources usually come from animals eaten, especially sea mammals and birds, or from driftwood abundantly scattered on beaches. Stone and mineral resources were collected at localized areas, often away from the shoreline, and therefore would hardly be determinants for more permanently occupied sites.

Considering only resource exploitation, we may expect coastal hunters and gatherers to arrange their villages at unequal intervals around these islands. More than an upper threshold number of villages per coastal length or people per village would strain the resource network too much, and population declines would result.

One measure of resource abundance might be the ratio of sites per total island perimeter. This may be expressed as the distance between sites. Given Amchitka's 73 sites and the estimated island perimeter of 194.7 km, we find an average intersite distance along the coast of 2.67 km. If we measure straight-line distances between adjacent sites, however, we find a mean intersite distance of 2.09 km and a range of 0.2 to 10.5 km. These figures, of course, ignore a time dimension in that not all sites were simultaneously occupied.

Defense. Veniaminof [1840, Vol. II, pp. 184-186 (cited in Hrdlička, 1945, pp. 144-148)] reports late prehistoric internecine contacts between islanders and describes defensive refuges as steep offshore islets providing temporary fortresses that were easily defensible. Coxe (1787, pp. 110-121), among others, describes early Aleut-Russian conflicts that amply demonstrate the Aleuts' warring abilities. Jochelson (1925, p. 23) reports that sites were chosen especially for their defensive potential in case of attack. But, as remarked above, Jochelson's interpretations of what coastal terrain constitutes appropriate habita-

tion sites is questionable. Still another question is whether a defense variable was important during the entire Aleutian occupation. Prehistoric warfare has not yet been identified in the archaeological record.

Most Amchitka sites are not located on narrow spits or points assuring easy escape by some "back way," nor are they usually found above high precipitous cliffs serving as natural defenses. It is clear from Veniaminof's record that the normal habitation site is not, at the same time, the defensive refuge, or "fort." Rather, such refuges were steep coastal spots or islets close to the village which offered protection only under attack. Therefore defensive elements, such as sheer cliffs and high elevation, were not normal determinants of midden site placement.

We note, however, that in contrast to Amchitka and other narrow islands, being able to escape attack by walking across the island to a friendly village is not possible on many islands. High volcanic cone islands would present a poor opportunity for cross-island travel. Hiding in high-elevation caves or other redoubts among interior rugged peaks would be an alternative in seeking safety.

DEMOGRAPHY

Aboriginal population cannot be ascertained directly but can be estimated on the basis of site size and ethnographic analogy to historic sites.

Amchitka site size distribution is given in Fig. 6, which is based on 1968 preliminary survey

figures. Sites are separated between high and low sites as previously described to discriminate relationships between site size and elevation. Sites vary widely in size from 25 to 2500 m². Eighty-three percent (59) of the sites are less than 800 m² in area. The most frequent size class is 200 to 300 m² for both high and low sites. There appears to be no positive correlation between size and elevation since the distributions of both high and low sites follow one another closely.

Another measure of population size or site duration is depth of cultural debris. Large or stable settlements should evidence greater depth than small or more transient ones. The majority of Amchitka sites have not been tested, and only depth approximations can be made. Of 72 sites for which depth has been estimated, we find a mean depth of 1.2 m and a range of 0.2 to 3.8 m. Only 15%, or 11 sites, have estimated depths of 2 m or greater. Unfortunately we have no comparable figures from other major islands with which to contrast these depth estimates.

On the basis of present estimates, there appears to be no correlation between depth and size of sites. This may be the result of inaccurate depth estimates, or it may mean that large village populations lived at settlements for a relatively short period. As will be demonstrated later, site size, if not depth, is helpful in deriving a site population.

Many educated guesses enter into the prehistoric population estimate for Amchitka and the other Rat Islands. If we look to the extant ethnohistoric literature describing early historic

Fig. 6—Histogram of Amchitka site size frequencies based primarily on 1968 site survey forms.

(AD 1750 to 1800) house and village sizes, we are confounded by two problems. First, most of the literature describing Aleut dwellings deals with the eastern islands. And, in late prehistoric times, the single-family *barabara* was replaced or supplemented by a much larger multiple-family *barabara* housing as many as 100 or more natives (Coxe, 1787, pp. 119 and 214; Lantis, 1970, pp. 172-174). The only fully excavated house in the Rat Islands is the 400-year-old wooden structure described earlier (Cook, Dixon, and Holmes, 1972, pp. 91-101), which was of single-family size. We have no direct evidence of the larger multiple-family houses occurring in the western Aleutians, although they may eventually be found. Therefore large multiple-family dwellings of the eastern islands cannot be meaningfully compared to small, single-family dwellings of the western islands during the late prehistoric and early contact period.

A second pitfall lies in taking village size during the late eighteenth or early nineteenth century Russian period as indicative of the precontact village size. As Jochelson (1925, p. 119) points out, the Russian colonists congregated the Aleut population at particular village locations for easier exploitation and administration. Population decline was great during the first 40 years of contact, and the population sizes of established Russian-period villages may not represent those of previous villages. Veniaminof (1840, Vol. II, pp. 202-203) does show that during 1825 to 1830 the average village size was 55, with a range between 13 and 196. Suggestions of Unalaska village size during the last quarter of the eighteenth century range between 32 and 45 (Lantis, 1970, pp. 173-174).

The number of persons per household, or single-family dwelling, times the number of houses provides one estimate of site population. But three factors cannot be controlled. We do not know exactly how many houses existed at a particular site, how many houses were simultaneously occupied, or how many persons lived in a house.

At this point the single excavated house from Site 32 is relevant. This wooden structure measures 6.0 by 7.5 m in outside dimensions (Cook, Dixon, and Holmes, 1972, pp. 91-101). This house occupies 45 m². If the upper midden area of the site in fact measures 300 m² as reported in the 1968 survey, then only seven houses of roughly equal size could fit into the site area. In fact, the excavators report seven depressions at this upper bluff area. We may only surmise the number of occupants living in the house, but, taking the bench sleeping area available, it would appear that six to eight adults would be a maximum number. None of the other six house depressions were

radiocarbon dated; so we cannot verify their simultaneous occupation.

However, let us speculate on some possible population sizes. If all seven houses held six to eight persons each, we would estimate the upper midden population at 42 to 56. The lower midden area next to the stream at Site 32 may or may not have been occupied at the same time. Cook, Dixon, and Holmes (1972, pp. 5-6) give no specific site sizes for either the upper or lower midden areas, nor do they indicate whether possible house depressions were found in the lower midden.

Since the most prevalent site size on Amchitka varies between 200 and 300 m², we might expect these settlements to have between 24 (four houses times six occupants) and 56 (seven houses times eight occupants) total population. If we assume that 45 m² is typical for Amchitka house space and that as many houses as possible will cover any site, then Amchitka's 73 sites (33,044 m²) should have about 734 total houses. Further, assuming six to eight persons per house and that all houses were simultaneously occupied, we arrive at an upper limit of between 4400 and 5900 persons for Amchitka.

Going beyond Amchitka, we noted above that about 37 (33%) sites should be found in the Rat group besides Amchitka's 73 (67%) sites. We have no accurate size estimates for non-Amchitkan sites, but, if we assume an equal population density, then we would estimate that an additional 2200 to 2900 persons occupied the other islands. This would bring the Rat Island total population to between 6600 and 8800. However, we have no current way of knowing how many sites were occupied simultaneously. Sample calculations for 100%, 50%, and 25% are as follows:

1. Rat population (100% of sites occupied concurrently): 6600 to 8800.
2. Rat population (50% of sites occupied concurrently): 3300 to 4400.
3. Rat population (25% of sites occupied concurrently): 1650 to 2200.

Which of these estimates is most realistic? If we accept the judicious opinions of Veniaminof (1840, Vol. II, p. 177), Lantis (1970, p. 174), and Polonskii (cited in Fedorova, 1973, p. 160) that the total precontact population for the archipelago fell somewhere between 12,000 and 15,000, then clearly the first estimate is too high. Because the Rat group constitutes only about 11% of the chain's total coastline, the lowest figure (1650) fits best if we assume a uniform relationship between number of sites and kilometers of coastline. If continued scholarship substantiates the approximate 15,000 chain maximum, our largest error in

calculating population is probably in assuming simultaneous site occupation.

Given at least 2500 years of Aleut occupation, the 25% rate seems reasonable for simultaneous site occupancy. On Amchitka this 25% rate could be accounted for in the following way. Eighteen sites of 61 persons each would comprise 1100 people (67% of the Rat Island population of 1650 and 25% of the Amchitka sites of 73). These 18 villages would be separated from one another by 10.8 coastal kilometers (based on the 194.7-km circumference). Every person would be dependent on an average coastline stretch of 0.18 km. Given the kinds of marine resources actually depended on and the sea space used, this area is realistic.

The preceding numerical speculations are presented as just that. But we need constantly to examine population variables to learn more about the ecological capacity to support human groups.

MARINE ADAPTATION AND EXPLOITATION PATTERNS

Aboriginal man living in the Aleutian chain had no choice but to depend on marine resources for survival. Food and raw materials came predominantly from the sea; a native could not survive on terrestrial organisms alone. Besides comprising the principal larder, the sea provided for transportation between island masses and was an important determinant of weather affecting those islands.

This section treats the manner in which man used the marine environment for food, raw materials, and travel. This utilization is organized through subsistence procurement systems, the direct interactions man had with marine ecosystems. Finally, an assessment of prehistoric man's impact on his physical and biological environment is also provided.

Resource Utilization

Habitats. Cultural adaptations to habitats and their associated biota dictate that hunters and gatherers shall live near the seashore in this and similar archipelagoes. The littoral zone and the open sea surface are by far the most important sources of food and raw material; inland terrestrial habitats contribute more raw materials than food.

Three major macrohabitats can be isolated with examples of particular habitats within these categories: (1) *open seas* (inshore and offshore zones; many distinctive areas discriminated on the basis of currents, tides, and waves), (2) *littoral zone* (sea cliffs, beaches, reefs, and islets or rocks; other areas discriminated on the basis of elevation, angle, rock structure, etc.), and (3) *terrestrial areas* (low ter-

racees or tablelands, mountains, lakes, streams; other zones discriminated on the basis of elevation, slope, drainage, etc.). All these habitats were exploited with differential intensity through the various procurement systems described later.

By using skin boats Aleuts maximized their exploitation of marine resources. Their mobility enabled them to sample more diverse marine habitats and prey species than any other competing Aleutian predator. Man could hunt sea mammals on the sea surface, catch fish deep beneath the surface, collect invertebrates from the intertidal zone, snare birds from a sea cliff, or dig roots in an island's interior. On any island or island group, then, man's exploitative capacity made him the most successful omnivore at the highest trophic level in the food web.

Aleuts were specialized in subsistence to the degree that procurement systems dealt with relatively few kinds of animals and plants. However, they were not so specialized that population decline was inevitable if one or two animal species failed to appear over a brief period. Within maritime limitations, Aleuts subsisted on a broad range of organisms in diverse habitats.

Water Travel and Resource Accessibility. Interaction among inhabitants of the Rat Island group was stressed in the introduction. The obvious mechanism for such interaction was interisland travel by skin boats. Whether by small kayaks (*baidarkas*) or large umiaks (*baidars*), male hunters and fishermen or entire families could exploit essentially all the Rat Island coasts and intervening and surrounding waters for food and raw material. We have demonstrated that not all the Rat Islands were inhabited as densely as Amchitka. However, all the islands were probably exploited for food and other materials to some degree. Although steep coastal profiles prevent persistent land occupations, these coasts may be abundant sea bird, sea mammal, and fish habitats. Further, skin boats not only open up more different kinds of habitats than those exploitable by land-bound hunters and gatherers but also make more similar habitats available. If one sea lion rookery or bird colony was temporarily vacant, then similar localities were available to the boatmen on the same or a nearby island.

Finally, in their skin boats Aleuts could travel with almost equal ease in any direction on the sea surface, weather permitting. Therefore, with good visibility between the Rat Islands, we must presume that boating between islands was as likely as travel around islands. Aleuts living on the northwestern end of Amchitka could reach Rat Island with less effort than paddling to the southeastern

half of Amchitka. Or Aleuts camped on the northwestern end of Kiska could cross to Segula for hunting quicker than they could travel to southwestern Kiska. A predilection to traveling around an island mass is consonant with a land-based world view but not to one based on full maritime adaptation.

Procurement Systems

Analysis of Aleut adaptation shows that there existed several major ways of procuring food and raw materials. Rather than applying a specialized technology and behavior pattern to procure each animal and plant species used, Aleuts transferred these patterns to several habitat-related species. These ways of subsisting or acquiring requisite materials from the environment are called procurement systems (McCartney, 1975, pp. 295-300). Flannery (1968) applied this same general ecosystem concept to Mesoamerican cultural development.

A system is conceived to be "an intercommunicating network of attributes . . . forming a complex whole" (Clarke, 1968, p. 42) or "a functioning set of elements that are interrelated so that change in one affects the others" (Redman, 1973, p. 16). And, of course, systems pertain in this instance specifically to networks or functional sets of procurement elements. As part of every procurement system, we find the following elements: (1) a habitat where sought-after organisms or materials occur; (2) the organisms or material proper; (3) the implements or tools used to extract the organisms or materials from the habitat (technology); (4) the dynamic extraction process; (5) the prerequisite knowledge and skill guiding the extraction process and application of technology (techniques); (6) the human procurers who singly or in groups represent larger kin or residential units as families or villages; (7) the food or raw-material products that emerge as usable input into subsistence, or the component parts of an extracted organism after additional processing (e.g., butchering); and (8) the time during which the preparation, extraction, and processing occur, or duration and seasonality. From the archaeological record, we only observe directly remains of organisms used, inorganic materials, and tools; but organisms and materials can usually be associated with particular kinds of habitats if not exact localities. Ethnographic and ethnohistoric documents shed light not only on tools but also on process (4), know-how (5), organization of hunting and gathering groups (6), resulting products (7), and amount of time and seasonality involved (8).

The usefulness of procurement systems as heuristic devices lies in their inclusion of (1) pri-

mary interacting elements into integrated wholes, (2) process or interaction between elements, and (3) ecologic relationships between cultural and biological spheres. These systems, though abstractions of human behavior, reflect as realistically as possible the manner in which Aleuts interacted with their islands and surrounding seas. They suggest the major subsistence themes and at the same time show the patterned, nonrandom behavior in relation to the environment. Procurement systems are the cultural adaptations or survival schemes that most directly and abundantly extract required nutrients and other resources from the environment. Systems are complex, and therefore we cannot analyze them reduced to their separable parts. In other words, the organization of the parts is the target for study. Finally, by integrating archaeological and ethnographic data, we can synthesize the bare archaeological finds into a dynamic cultural process.

Aleutian Procurement Systems. Aleutian procurement systems, as typical of most held by hunters and gatherers, are largely determined by habitat, seasonal occurrence of important species, and specific animal behavior. As a result, Aleuts had relatively little latitude for effectively manipulating their environment. They raised no crops, kept no domesticated animals with the possible exception of dogs, and had no sure method of food storage. Their adaptive flexibility lay not in juggling a particular system but in switching systems if one failed to produce necessary food or materials.

Eight procurement systems are tentatively suggested for the Aleutian chain. These systems fall in inclusiveness between higher level divisions (hunting, fishing, and gathering) and lower level divisions (e.g., winter sea otter hunting, summer halibut fishing, etc.) and are a compromise in degree of specificity. These eight systems reflect the majority of procurement patterns for the entire chain, although some island population will be expected to deviate slightly from these as local conditions demand.

Although these systems have been distilled from historic-period literature, they are thought to have considerable antiquity. Because the archipelago falls beyond the southerly limit of west Alaskan drift ice and is dominated by maritime climate rather than continental climate, temperature and other weather fluctuations over the past several millennia probably caused only minor deviation from today's pattern. Modern biota are shown in the midden debris to have had very little change in character for thousands of years. Therefore procurement methods are presumed to have been relatively stable as well.

The Aleutian procurement systems and major habitats are as follows:

Hunting:

1. Sea mammal hunting offshore (inshore and offshore waters).
2. Sea mammal hunting onshore (active beach, low terrace, islets, or rocks).
3. Bird hunting on water (inshore, offshore, lagoons, and inland lakes).
4. Bird hunting on nesting sites (sea cliffs and other island margins).

Fishing:

5. Fishing offshore (offshore waters from boat).
6. Fishing onshore (stream mouths and inshore waters with hook and line or nets).

Gathering:

7. Intertidal and beach collecting (active beaches and intertidal zones or reefs).
8. Onshore collecting (sea cliffs and island interiors).

Figure 7 illustrates a composite habitat profile indicating where the systems interact. Figure 8 illustrates these systems as part of a total ecosystem equilibrium model; likely causes of disequilibrium are also indicated.

Fig. 7—Composite profile of an island edge showing habitat locations of the major procurement systems described in the text.

In Fig. 8 food primarily and raw materials secondarily affect the population of a region like the Rat Islands. Feedback adjustments are shown with food supply controlling extraction techniques and raw materials controlling technology. In other words, amounts of food directly limit (—) or expand (+) the intensity of food exploitation through the eight systems. With the exception of system 8, raw materials are usually derived from the by-products of food animals extracted through the remaining seven systems. Therefore feedback (0) to technology shows the flow of animal by-products to finished tools rather than suggesting that a shortage of raw materials will intensify extraction systems to provide those supplies. Probably small amounts of food and/or raw materials derive from exchange or trade of a formal or informal nature. This input and output is diagramed to reflect such flows of goods (see Cultural Patterns and Interaction section).

The double arrows between habitat and techniques reflect the interaction between these two elements; the effects of man's exploitation of the various habitats are outlined below.

The population of a village or community, however transitory, is largely a function of food

Fig. 8—Schematic representation of Aleutian procurement systems and their interrelationships. Local or regional population equilibrium results from the successful exploitation of marine and terrestrial habitats; disequilibrium or population decline results from environmental effects shown at the top of the diagram.

and raw materials to meet the needs of sustenance, shelter, and mobility. An important consideration in our model is that isolation from external cultural influence and insulation from vagaries in food supply (based on relatively stable marine habitats) translate into a relatively stable human population. The human carrying capacity is high as are all Pacific coastal groups because of abundant marine resources. Population size will also reflect the minimum food supply rather than the maximum amount available during the most productive season, or potential population adjusts to the minimal food supply (late winter and early spring) to sustain the population through the annual cycle. The effects of positive feedback are therefore restrained by habitat and organism limits.

Disequilibrium or a decrease in population can result from three areas of influence. Such inter-related physical phenomena as ashfalls, earthquakes, and tsunamis, characterizing the Pacific Ocean rim, can quickly interrupt normal marine and terrestrial ecosystems by altering habitats or causing massive die-offs. Bad weather, certainly a relative term in the Aleutians, can restrict exploitation by keeping Aleuts off the ocean surface; or slow to rapid and transient to permanent shifts in animal ranges can affect available food and raw-material resources. Finally, diseases, group accidents, and warfare can affect population directly by killing natives or by indirectly making it impossible for dependents to survive without primary providers in the family. Unfortunately evidence of such disequilibrium is difficult to detect in the archaeological record. The most massive and best-known state of disequilibrium resulted from Aleut-Russian contact of the eighteenth century when disease and genocide were particularly acute.

Table 5 summarizes the major techniques and implements used in procurement. This table places many archaeologically derived artifacts into activity spheres or contexts which stress their use rather than form. Figure 8 shows the kinds of products that result.

Rat Island Systems. How well do these eight systems describe prehistoric subsistence and ecologic exploitation in the Rat Islands? They appear to be the best models we have at present.

Note that the citation examples in Table 5 span 200 years since Russian contact and specifically describe procurement techniques from throughout the chain. There is a preponderance of examples from the eastern islands for which we have more sources, but we find subsistence uniformity throughout the chain and over time largely because the physical environment and biota are fairly uniform throughout. Of course, minor abundance

variations will occur from island group to island group, but differences are considered here much less significant than general uniformity. Because the Rat group constitutes a major segment of this archipelago, the presumption here is that prehistoric Aleuts in that group participated in these systems as much as did any other island group population.

The archaeological record at least shows the use of the procurement implements included in Table 5 rather than some radically different tool assemblage. We cannot, as yet, derive total systems from the archaeological records. However, since the Rat Island artifacts, features, settlement patterns, habitats, and species correspond closely to those of other parts of the chain, we can safely assume that past exploitation techniques also conformed to the Aleutian subsistence pattern, which is the total of these eight individual systems.

Rat Island Food and Material Resources

Food. Consider the food limitations of aboriginal Aleuts. [See Zimmerman (1963, p. 57) for similar native food restrictions in the Hawaiian Islands as typical of other Pacific island groups.] There are no terrestrial mammals found west of Unimak Island and the tip of the Alaska Peninsula besides foxes, lemmings, mice, and shrews (Clark, 1945, pp. 48-49; Murie, 1959), and even these were not to be found in the Rat Islands. No domesticated crop plants were known, and the damp climate precluded storing dry plant products for long periods. Unlike the Alaskan interior, which has relatively high summer temperatures, the small island masses of the Aleutian chain are dominated by the cold north Pacific Ocean waters with summer temperatures of about 40°F. Amchitka is about the southernmost point in Alaska, but the sea environment negates any appreciable summer warmth. Low insolation may be equally as important as temperature in limiting plant growth.

The few native plants that do cover the islands provide little caloric input, and these are only available during the summer months.

Thus sea resources, directly or indirectly, become human food staples. Sea mammals, fish, and marine invertebrates variously provide meat, blood, and fat. Marine algae are a source of vegetable matter. The most important birds by size and abundance are those dependent on marine organisms. Terrestrial plants, as mentioned above, are controlled by a maritime climate. Survival in the chain, then, depends on some mix of hunting, fishing, or gathering these marine-related organisms over the annual cycle.

Table 5—Procurement System Techniques and Implements

1. System: Sea-mammal hunting offshore**Techniques**

Sight and surround animal with boats; tire diving animal (except large whales); harpoon and spear animal or club it in water; large whales wash ashore when dead, but smaller sea mammals must be dragged or carried to shore.

Implements

Kayak/umiak (paddles and oars, sucking-tube bailers, sponges, gut kamleika suit,* wooden visor hat, stone ballast, and other boat accoutrements).

Harpoon (toggle head with end blade or point, loose shaft, socket piece, wooden shaft, long thong line, and bladder float or nontoggling but detachable harpoon head with barbs, sometimes with end blades or points, socket piece, wooden shaft, long thong line, and bladder float).

Spear/lance (nondetachable barbed head, often with end blade or point, socket piece, and wooden shaft).

Harpoon dart (nontoggling harpoon head, socket piece, wooden shaft, some with feathers, and thong line between head and shaft; propelled with throwing board).

Club.

References

Cook, Clerke, and Gore, 1818, p. 37; Coxe, 1787, pp. 62, 87, and 120; Elliott, 1886, pp. 140-141, 151-152; Heizer, 1943, 1960, p. 134; Jochelson, 1933, pp. 11, 24-25, and 55-58; Langsdorff, 1817, pp. 340-343; Ransom, 1946, p. 614; Sarichev, 1807, p. 74; Turner, 1886, pp. 200-201; VanStone (Choris), 1960, pp. 155-156; Veniaminof, 1840, Vol. II, pp. 105-106, 132-133, 217-225, 231, 245-248, 342-344, 388, and 395-396.

2. System: Sea-mammal hunting onshore**Techniques**

Surprise seals, sea otters, or sea lions on island shore or on islets or rocks; hunters approach by foot or boat, depending on locale; kill animals by harpooning, spearing, or clubbing; possibly nets for entangling used prehistorically; decoy seals.

Implements

Kayak/umiak (as in sea-mammal hunting offshore).

Harpoon, lance and/or spear (as in sea-mammal hunting offshore).

Club.

Net.

(Decoy).

References

Elliott, 1886, pp. 142-144 and 366-368; Veniaminof, 1840, Vol. II, pp. 344-345, 362-363, 383-384, and 388.

3. System: Bird hunting on water**Techniques**

Stalk birds resting on sea surface or lakes or surfacing; capture birds by darting with leister† or shooting with arrow; kill birds by breaking their necks; secondarily, net birds on lakes from blind.

Implements

Kayak/umiak (as in sea-mammal hunting offshore).

Leister darts (multiple-pronged wooden darts propelled with throwing board).

Bow and arrow (barbed head or point, usually with no end blade, wooden shaft with feathers; short wooden bow).

(Net with trip line).

References

Cook, Clerke, and Gore, 1818, p. 37; Coxe, 1787, p. 215; Jochelson, 1933, p. 11; Sarichev, 1807, p. 74; Turner, 1886, p. 140.

4. System: Bird hunting at nesting sites**Techniques**

Sheer bird cliffs approached by boat from below or from above by rope; snares set at burrow entrances or on ledges where birds perch; strangled or snared birds collected later; or birds clubbed on nest or caught with hands and killed by breaking their necks; bolas, handnets, and leisters used to down flying birds around rookery; birds also captured away from the nesting areas.

Implements

Kayak and/or umiak (as in sea-mammal hunting offshore).

Ropes of thong or seaweed.

Collecting container of woven grass or stretched gut.

Snare.

Club.

Bolas (stones and thong).

Hand net/loose net.

References

Coxe, 1787, p. 86; Elliott, 1886, p. 209; Jochelson, 1933, pp. 8, 10, and 53; Sarichev, 1807, p. 70; Staehlin, 1774, p. 28; Turner, 1886, pp. 117-118, 130, 137, and 141; VanStone (Choris), 1960, p. 155.

5. System: Fishing offshore**Techniques**

Fishing from boats with hook and line or sometimes spearing with leister spears; club used to kill large fish (halibut).

(Table continues on page 82.)

Table 5—(Continued)

Implements	
Kayak/umiak (as in sea-mammal hunting offshore).	
Fish line (bone one- or two-piece fishhook, long seaweed and/or kelp or sinew line, stone weight).	
Leister spear (multiple prongs on wooden shaft).	
Club.	
References	
Cook, Clerke, and Gore, 1818, p. 37; Coxe, 1787, pp. 82, 87, and 215; Elliott, 1886, pp. 168 and 212-213; Jochelson, 1933, pp. 5, 8, 11, and 51; Langsdorff, 1817, pp. 333-334; Turner, 1886; Veniaminof, 1840, Vol. II, pp. 248-249.	
6. System: Fishing onshore	
Techniques	
Fishing with hand lines from shore; catching salmon, Dolly Varden trout, and other massed fish at stream mouths with nets, leisters, and with hands; dams and weirs sometimes used.	
Implements	
Net of sinew or vegetable material (large nets used with stone weights and possibly wooden floats).	
Fishing line (as in fishing offshore); sometimes used with bladder floats for sets.	
Leister spears (as in fishing offshore).	
(Kayak/umiak possibly used prehistorically in setting nets out from a beach).	
References	
Cook, Clerke, and Gore, 1818, p. 37; Coxe, 1787, pp. 62 and 82; Jochelson, 1933, pp. 7, 11, and 51-52; Ransom, 1946, p. 608; Sarichev, 1807, p. 71; Turner, 1886; Veniaminof, 1840, Vol. II, pp. 248-249.	
7. System: Intertidal and beach collecting	
Techniques	
Combing exposed reefs and intertidal shores for urchins and other marine invertebrates and algae; combing active beaches for washed up sea mammals, birds, fish, and driftwood.	
Implements	
Prying implements for removing shellfish and invertebrates from rocks.	
Grass baskets or stretched gut containers (adze, maul, and wedge for sectioning logs on the spot).	
References	
Elliott, 1886, pp. 214-215; Jochelson, 1933, pp. 8 and 11; Ransom, 1946, pp. 609-611 and 616-617; Staehlin, 1774, pp. 29 and 36-37.	
8. System: Onshore collecting	
Technique	
Collecting terrestrial plant materials, bird eggs,† stone tool materials, minerals, etc., from specific localities landward from the active beach.	
Implements	
Baskets, nets, and other containers.	
Cordage (sinew or grass for bundling gathered materials).	
Mattock (bone head hafted to wooden handle).	
Unhafted probe or digger.	
Maul (stone hammerhead hafted to wooden handle; for breaking up stone materials).	
References	
Cook, Clerke, and Gore, 1818, pp. 39-40; Coxe, 1787, pp. 62, 69, 86, 196, and 213; Elliott, 1886, pp. 148, 168-169, 181, and 222; Jochelson, 1933, pp. 7-8, 10-11, and 59-63; Langsdorff, 1817, pp. 334-335 and 343; Ransom, 1946, pp. 613 and 619; Sarichev, 1807, p. 70; Turner, 1886; Veniaminof, 1840, Vol. II, pp. 94-95, 109, 229, and 232-233.	

*Waterproof parka of stretched gut.

†Spear with multiple side or end prongs.

‡It may be argued that bird egg collecting from bird colonies on shore should be placed under bird hunting at nesting sites rather than here, especially if techniques of habitat exploitation are stressed.

I have summarized the Aleut food sphere elsewhere (McCartney, 1975, p. 315) and restate the conclusions here. Besides the fact that food staples are of marine origin, with sea mammals, fish, and birds providing the greatest input, most of these foods are also transient and are only found at particular times during the year. Because of the cyclical and sometimes migrating nature of the fauna and the sharp seasonality of the flora, there is an uneven food supply from one month to the next. At the poorest month (about March), "crisis" foods, such as shellfish, sea urchins, and algae,

become especially important for survival into the next productive period. Part of this low ebb of food is due to inadequate storage techniques for preserving seasonal foods into later months. Fat or oil from sea mammal blubber is a necessary part of the diet; a constant diet of lean meat or vegetable products does not provide the requisite caloric fuel for survival. Finally, the annual dependency on marine resources from small shellfish to the largest whales plus such incidentals as land plants demonstrates how Aleuts had to exploit their total archipelago environment.

Many of the above characteristics may also apply to Northwest Coast Indian groups. According to Piddocke (1965, p. 247):

...the abundance of the resources of the Kwakiutl has been somewhat overestimated and its significance misinterpreted. It was great enough to support a population larger than the usual size reported for hunting and gathering societies; but this population lived sufficiently close to the margins of subsistence so that variations in productivity which fell below normal could threaten parts of the population with famine and death from starvation.

Just as "starvation was no stranger to the Kwakiutl" because of "prolonged periods of bad weather which prevented hunting and fishing, and the failure of fish runs," so Aleutian starvation was known for much the same reasons (Veniaminof, 1840, Vol. II, p. 186, cited in Petroff, 1884, p. 151; Jochelson, 1925, p. 43; 1933, pp. 8 and 11).

Fauna from only one Aleutian site has been studied for quantitative estimates of food consumed. Denniston (1972, pp. 180-220) calculated the amounts of protein, carbohydrates, fats, and kilocalories available from the Ashishik Point (Umnak) faunal collection. She also computed the relative amounts of food that could have been derived from the major types of animals represented in her excavation units. Weights of edible products derivable from invertebrates, birds, fish, and sea mammals were in the ratio of about 1 : 2 : 36 : 52, respectively. This ratio does not necessarily hold for the relative amounts of protein, carbohydrates, and total calories supplied by the different animal groups, but still it is a more precise estimate of the Aleut diet than that suggested by the ethnohistoric literature (McCartney, 1975, pp. 293-295). This ratio of 1 : 2 : 36 : 52 for the various food sources is our best estimate of relative source importance for the entire chain, including, of course, the Rat Islands.

Table 6 lists the identified faunal organisms from Rat Island sites and from Near and Andrea-nof sites for comparison. Most of the faunal debris has not been studied quantitatively, nor have all low-frequency species been identified. Sea mammals and birds particularly were used not only for food but also for raw materials (skins, feathers, gut, bones, teeth, etc.), and some species may have been gathered more for one requirement than for the other. A comparison between these Rat Island species and a more complete listing of Aleutian species known to have been utilized aboriginally (McCartney, 1975, Table 1) shows a high correspondence. All species considered to be important because of their size and/or number are found in the few Rat Island sites sampled. We find substantiation therefore for the uniformity of faunal ex-

ploitation throughout the chain and, by implication, the uniformity of techniques required in procuring these species.

Materials. Aleuts used a wide range of raw materials for their tools, clothing, decoration, boats, houses, and other equipment for adapting. Three major categories with types of material and some finished products are given in Table 7.

Archaeological remains are usually stone, bone, and tooth, and only occasionally water-soaked wood (for wood, see Cook, Dixon and Holmes, 1972; Turner, 1973, p. 9).

Besides driftwood and stone (systems 7 and 8), most of these raw materials for manufacturing are primarily from sea mammals and secondarily from birds. An example of the intensive utilization of sea lions and resulting materials is described by Elliott (1886, pp. 369-370).

Island Resource Locations. The Rat Islands vary today in richness and abundance of species, and this disproportionate distribution undoubtedly occurred in the past. This section outlines the major resources available on the various islands as a suggestion of probable prehistoric exploitation. However, several considerations should be kept in mind in reviewing resource localities.

1. We cannot presume that modern faunal distribution exactly matches that of several thousands of years ago. Modern distribution data, however, provide the best indication of past fauna available. Since animals pursued are habitat specific, we know that there is no random distribution of sea mammals, fish, birds, invertebrates, algae, and terrestrial plants today or in the past. Modern habitat locations are assumed to correspond closely to past locations on the same island.

Population sizes for most of the species hunted, fished, or gathered have not been drastically reduced from the prehistoric period with the exception of whales and pelagic fish, which are taken by the high-seas fisheries. Sea otter populations have rebounded in the Rat Islands since they were placed under protection in 1911, and harbor seals and sea lions have not been exploited for pelts in a way comparable to the controlled fur seal harvesting in the Pribilofs. Except for islands on which foxes are found, bird colonies are relatively free of disturbances. Marine invertebrates, algae, and terrestrial plants are thought to be essentially unchanged since the prehistoric period. Because Aleuts have not depended on these major food animals for over half a century and because the Aleut population over that period was but a small fraction of the prehistoric population size, Aleuts have probably not seriously affected faunal totals in recent years.

Table 6—Identified Faunal Remains from Rat Island Midden Sites

Species	Rat Island sites			Comparative sites	
	Amchitka Site 31 (Desautels et al., 1971, pp. 314-340)	Little Kiska and Amchitka (Hrdlička, 1945, pp. 613-616)*	Little Kiska (Friedman, 1937)†	Attu, Amchitka, Adak, and Kiska (Dall, 1877, p. 50)‡	Attu and Atka (Jochelson, 1925, pp. 25, 27-29)§
Sea mammals					
Sea otter (<i>Enhydra lutris</i>)	59% of sea mammals (744)¶	X (common) L. Kiska**			X Attu, Atka
Hair or harbor seal (<i>Phoca vitulina</i>)	33% of sea mammals (418)	X (most abundant) L. Kiska		X	X Atka
Northern sea lion (<i>Eumotopias jubata</i>)	6% of sea mammals (79)	X (common) L. Kiska		X	X Attu, Atka
Northern fur seal (<i>Callorhinus ursinus</i>)	2% of sea mammals (30)	X (common) L. Kiska		X	? Attu, Atka
Walrus (<i>Odobenus rosmarus</i>)		X (1 bone) L. Kiska		X	
Pacific harbor porpoise (<i>Phocoena vomerina</i>)		X (occasional) L. Kiska		X	
Dall porpoise (<i>Phocoenoides dalli</i>)		X (occasional) L. Kiska			
Whales	X			X	X Attu, Atka
Land mammals					
Dog (<i>Canis familiaris</i>)		X (5 innominates) L. Kiska			
Fish					
Rock greenling (<i>Hexagrammos lagocephalus</i>)	X (abundant)				X Attu
Red Irish lord (<i>Hemilepidotus hemilepidotus</i>)	X (abundant)				
Pacific cod (<i>Gadus macrocephalus</i>)	X (abundant)			X	X Attu, Atka
Pacific halibut (<i>Hippoglossus stenolepis</i>)	X			X	X Attu, Atka
Rockfish (<i>Sebastes</i> sp.)	X				
Salmon (<i>Oncorhynchus</i> sp.)				X	
Unidentified herring, sculpins, and flounder				X	X Atka
Marine Invertebrates (in descending order of Site 31 abundance)					
Green sea urchin (<i>Strongylocentrotus</i> sp.)	X	X (very abundant) Kiska and L. Kiska		X	X Attu, Atka
Limpet (<i>Acmaea scutum</i>)	X	X Amchitka		X	X Attu, Atka
Limpet (<i>Acmaea pelta</i>)	X	X Amchitka		X	X Attu, Atka
Blue mussel (<i>Mytilus edulis</i>)	X	X Amchitka		X	X Attu, Atka
Giant horse mussel (<i>Modiolus modiolus</i>)					X Attu
Mussel (<i>Modiolus vulgaris</i>)				X	
Butter clam (<i>Saxidomus giganteus</i>)				X	X Atka
Bent-nosed clam (<i>Macoma nasuta</i>)				X	
Clam (<i>Macra ponderosa</i>)					X Attu, Atka
Pearly monia (<i>Pododesmus macroschisma</i>)	X				
Black katy (<i>Katharina tunicata</i>)	X				X Attu

Hairy triton (<i>Fusitriton orgeonense</i>)	X				
Sitka periwinkle (<i>Littorina sitkana</i>)	X	X Amchitka		X	X Attu
Channeled dogwinkle (<i>Thais canaliculata</i>)	X				
? (<i>Thais lima</i>)		X Amchitka		X	
Island scallop (<i>Calamys islandicus</i>)	X				
Northern opal-shell (<i>Epitonium wroblewskii</i>)		X Amchitka			
Rock cockle (<i>Protothaca staminea</i>)				X	
Whelk	X				
? (<i>Volutopsius rebularis</i>)	X Amchitka				
? (<i>Collisella pelta</i>)				X	
Barnacle (<i>Balanus</i> sp.)	X				
Birds (by family, in descending order of Site 31 abundance)					
Phalacrocoracidae (cormorants)	37% of first 6 families (250)	X (occasional) Amchitka	24% of bird bones (132)		X Attu, Atka
Anatidae (swans, geese, ducks)	35% of first 6 families (235)	X (abundant) Amchitka	34% of bird bones (185)	X	X Attu, Atka
Alcidae (murres, murrelets, auklets, puffins)	11% of first 6 families (77)	X (rare occasional) Amchitka	22% of bird bones (118)	X	X Attu, Atka
Procellariidae (shearwaters, petrels)	7% of first 6 families (47)	X (occasional) Amchitka	X (2 bones)		X Attu
Diomedecidae (albatrosses)	6% of first 6 families†† (36)	X (common) Amchitka	12% of bird bones (68)	X	X Attu, Atka
Laridae (gulls, terns)	4% of first 6 families (28)	X (rare) Amchitka	3% of bird bones (16)	X	X Attu
Gaviidae (loons)	X (less than 4% each)		1% of bird bones (6)		
Podicipedidae (grebes)	X				
Falconidae (falcons)	X				
Accipitridae (eagles)	X		1% of bird bones (3)	X	
Corvidae (ravens)	X	X (rare) Amchitka	3% of bird bones (15)		
Strigidae (owls)			X (1 bone)		
Fringillidae (sparrows, longspur, buntings)					X Attu

*Little Kiska Site at west end of the island, sampled in 1936; Amchitka Sites 2 and/or 3, sampled in 1938; birds = 10 species.

†Friedman's Little Kiska sample is that excavated by Hrdlička in 1936; 34 species; R = 1-132; the following 7 species total 408 bones (75%) in descending order: Pelagic Cormorant, Pacific Eider, Short-tailed Albatross, Emperor Goose, Horned Puffin, Crested Auklet, and Tufted Puffin.

‡Dall does not specifically identify the source of his material; at least some comes from Amchitka and/or Kiska; with the exception of urchins, the remaining invertebrates "do not form altogether more than one-tenth of one per centum of the stratum."

§Jochelson's specimens from Attu and Atka; frequencies not specified.

¶Individual bones, not individual animals; whale fragments not included in counts.

**No details about Hrdlička's Amchitka faunal samples, but sea otter and harbor seal are the most abundant sea mammals.

††Turner (1970, p. 121) also notes the abundance of albatross bones in Amchitka middens.

The modern distribution and census figures for these animals and plants, then, ought to be a clue to their location and relative abundance in the past.

Table 7—Major Raw Materials and Important Products

Vegetable	
Driftwood	Boat frames, house frames, burial sarcophagi, harpoon shafts, clubs, bowls, trays, spoons, handles, throwing boards, masks, and some firewood.
Grass	Baskets, mats, cordage, nets, cloaks, house coverings, lining, and insulation material.
Twigs	Fuel and cushioning.
Kelp/algae	Fishing and other lines.
Other	Dyes and medicinal herbs and plants.
Animal	
Skins	Clothing and boat coverings.
Gut/internal organs	Kamleikas, windows, containers, drumheads, and harpoon floats.
Sinew	Nets and cordage for lines and lashing.
Bones	House frames, boat pieces, tools, weapons, spoons, and containers.
Teeth	Tools, decoration, and gaming pieces.
Feathers	Decoration.
Whiskers	Decoration.
Blubber	Lamp oil and waterproofing for skins.
Blood	Glue.
Inorganic	
Ocher and/or other minerals	Paint.
Sulfur	Fire starting.
Stone	Tools, bowls, lamps, weights, ornaments, fish weirs, house foundations, boat ballast, and storage-pit liners.

2. Island size and species abundance are not always proportional to one another. Sufficient evidence of this is seen in the size of Buldir's sea lion colony or Khvostof's and Davidof's puffin colonies (see Table 8).

3. Because fish and sea mammals are the two most important food sources, we can only partially estimate their abundance by observing animals from shore. In other words, Aleuts were often

seeking the best hunting and fishing waters (systems 1, 3, 5, and 6), not the land masses with the most organisms on shore. Whales and porpoises are always water bound, and migrating fur seals rarely haul up while moving through the chain's passes. Sea otters and harbor seals are so wary that they are less frequently surprised on shore than encountered in the water. Because these species cannot be fixed to an island but rather are fixed to specific water habitats, we realize that shore counts can only suggest abundance for a surrounding water space or for species procured from shore (systems 2, 4, and 7).

Table 8 summarizes the present-day distribution and abundance of the major Rat Island resources that were important items of subsistence for prehistoric Aleuts. Because not all the islands have been surveyed with equal intensity for comparable species, only a few generalizations can be derived from the present quantitative data. Occurrence only is considered in Table 8, and seasonal variation is ignored; maximum animal population estimates are given rather than minimums or means. For the most part, all these species are recognized in prehistoric midden debris (Table 6).

A few generalizations are as follows: (1) The best sea lion islands are, in order, Buldir, Semisopochnoi, Kiska, Amchitka, and Rat. (2) The most sea otters are found around Amchitka, Kiska, and Rat Islands. (3) The best harbor seal island is probably Amchitka. (4) Fur seals may have been more abundant on and around Buldir if that suggested rookery is accurately identified (Table 8). (5) Most colony birds, except puffins, which center on Khvostof and Davidof, and cormorants, which center on Amchitka, are concentrated on Buldir. (6) Duck and geese estimates are available only for Amchitka, but, because these birds primarily occupy littoral waters or shores, they should be most abundant on islands with the greatest perimeter [Amchitka (195 km) and Kiska (161 km) stand out in shoreline length]. (7) Stream runs of salmon and Dolly Varden are probably most abundant on Amchitka, Kiska, Rat, and Semisopochnoi, roughly in that order; no comparative measures of major inshore and off-shore fish species are available. (8) Major differences in whale, fish, invertebrate, algae, terrestrial plant, and driftwood distribution are unknown; the last four could be grossly compared by island size and circumference. (9) No land mammals, with the possible exception of dogs, are known on any of the islands preceding Russian rats and later introductions. (10) Although sulfur was limited to Little Sitkin, Khvostof, and Davidof, volcanic ejecta is more abundantly distributed; basalt and

Table 8—Major Rat Island Resources

Organic Resources	
Sea mammals	
Sea lions: Estimates given in descending order. Buldir, 3450; Semisopochnoi, 1590; Kiska, 1470; Amchitka, 900; Rat, 570; Little Sitkin, 335; Segula, 250; Rat Island total, 8565; major rookeries fairly evenly spaced around any one island; many offshore rocks and islets have sea lions; usually stay in waters of <50 fathoms (Kenyon and Rice, 1961; Kenyon and King, 1965; Sekora, 1973).	
Sea otters: Estimates for 1965 given in descending order. Kiska, 1652; Amchitka, 1525; Rat, 435; Semisopochnoi, 271; Little Sitkin, 180; Segula, 75; Khvostof and/or Davidof, 52; Buldir, 30; other Amchitka estimates: about 1961, 4000 to 7000; 1970, 4000; 1970–1972, 7601; Rat Island total, 4196+; Rat and Delarof Islands total, 23,000 to 32,000; almost all islands have sea otters offshore, especially in waters of <30 fathoms and where kelp beds are extensive. (Kenyon, 1969; Spencer, 1969; Estes and Smith, 1973; Sekora, 1973).	
Harbor seals: Amchitka has an estimated 1200; other Rat Islands combined have 1600; usually found in waters of <30 fathoms (Sekora, 1973).	
Fur seals: Rarely haul up in the Aleutians when migrating through to and from Pribilofs; only known possible Aleutian rookery is Buldir; only hunted offshore in other areas; most fur seals use eastern rather than western island passes (Murie, 1959; Sekora, 1973).	
Birds	
Auklets: Total Rat Island estimate, 631,000; individual island totals given in descending order: Kiska, 125,000 to 400,000; Segula, 70,000; Buldir, 40,000 (Sekora, 1973).	
Murres: Total Rat Island estimate, 30,600; individual island estimates: Buldir, 30,000; Semisopochnoi, 700 (Sekora, 1973).	
Puffins: Total Rat Island estimate, 28,000; individual island totals given in descending order: Davidof, 7720; Khvostof, 6540; Semisopochnoi, 2200; Pyramid Island (near Davidof), 1500; Amchitka, 1300; Kiska, 1000+ (Sekora, 1973).	
Kittiwakes: Total Rat Island estimate, 40,000; Buldir, 35,000 (Sekora, 1973).	
	Gulls: Total Rat Island estimate, 6500+; Buldir, 5000; Amchitka, 3000 (Williamson and Emison, 1969; Sekora, 1973).
	Cormorants: Total Rat Island estimate, 2400; Amchitka, 1600; Semisopochnoi, 700 (Williamson and Emison, 1969; Sekora, 1973).
	Fulmars: Total Rat Island estimate, 250 (Sekora, 1973).
	Harlequin Duck: Amchitka total, 3500 (Williamson and Emison, 1969).
	Common Eider: Amchitka total, 1500 (Williamson and Emison, 1969).
	Emperor Goose: Amchitka total, 5000 (Williamson, Emison, and White, 1971).
	Common Goldeneye: Amchitka total, 4000 (Williamson and Emison, 1969).
	Bufflehead: Amchitka total, 2000 (Williamson and Emison, 1969).
	Rock Ptarmigan: Amchitka total, 1800 (Williamson and Emison, 1969).
	Fish
	Salmonids: Approximate number of streams potentially suitable for salmon, in descending order: Amchitka, 30; Kiska, 27 plus 2 lagoons and 3 landlocked lagoon lakes; Rat, 7; Semisopochnoi, 7; Segula, 3; Little Sitkin, 3; Little Kiska, 3; Buldir, 1; Khvostof, 1; Davidof, 0; Amchitka has 21 streams supporting pink and a few coho salmon plus Dolly Varden; red salmon are known from Semisopochnoi; Kiska supports coho and probably pink salmon plus Dolly Varden in at least three areas (USGS Bulletin 1028 maps; Neuhold, Helm, and Valdez, 1971; A. C. Hartt and C. A. Simenstad, personal communication, 1974).
	Inorganic Resources
	Sulfur: Large deposit on Little Sitkin; sulfurous fumaroles on Little Sitkin, Davidof, and Khvostof; for fire making (personal observation; Sekora, 1973).
	Pumice/scoria ejecta: Semisopochnoi, Little Sitkin, Davidof, Kiska, Segula, and Buldir probably all have surface pumice and/or scoria for abraders and other implements (Sekora, 1973; L. M. Gard, written communication, 1974).
	Lignite: Amchitka; for labrets and other carved ornaments (Sekora, 1973; L. M. Gard, written communication, 1974).

argillite have an even wider distribution; no obsidian source is known.*

From these distributional data, sketchy as they are, we conclude that sea mammal, fish, and bird foods and materials are more abundant on Buldir, Amchitka, Kiska, Semisopochnoi, and Rat Islands.

*L. M. Gard (written communication, 1974) states that obsidian is common in the upper part of the Amchitka Formation (see Chap. 2) but is unsuitable for tool manufacture because it tends to shatter into small pieces. The rarity of obsidian in Amchitka artifact collections confirms the unsuitability of local obsidian.

Because Buldir was so isolated and afforded only limited coastal living space, however, it attracted few, if any, permanent human residents. The interrelated dimensions of island size, circumference, and irregularity appear to determine abundance of primary species except for Buldir. Buldir's sea mammal and bird populations may be a function of isolation where scarcity of land concentrates populations. Inorganic materials as a group are more localized than are organic materials. A resource such as sulfur lends itself to trade because its acquisition can be more closely controlled.

Human Impact on the Environment

All the evidence one can muster suggests that prehistoric Aleut occupation throughout the chain had little lasting impact on island terrain. Remaining testimony of past physical alteration is limited to such slowly decaying features as house ruins, midden debris, burial sarcophagi, or mummy burials in caves and crevasses. If unbuffered by thick calciferous deposits (urchins, shellfish, mammal, and bird bones) or not waterlogged, organic materials quickly decay, leaving little or no residue. Thus the most apparent relics of past occupation one notes today are the coastal midden sites, which are covered with luxuriant vegetation because of their added soil nutrients. As pointed out in the introduction, the ancient village remains are rather insignificant compared with modern excavations and land-surface alterations.

Unlike Eskimos of the Canadian Arctic, who built so many features of stone (e.g., burial cairns, boat supports, markers, meat caches, etc.), Aleuts rarely used beach boulders except for house-wall foundations. Driftwood was the abundant raw building material, and, unless covered with sod and waterlogged, pieces would soon blow away or decay.

Aleut impact on past biota, however, is more difficult to evaluate and can only be postulated. The first colonization by man of the chain, as yet poorly documented archaeologically, undoubtedly had a significant impact on various species incorporated into the contemporary procurement systems. Nonetheless, we have no pre-man baseline against which to judge man's initial effects. If species easily preyed on by man were present in the western Aleutians, such as the sluggish northern sea cow and the flightless spectacled cormorant, both found in the Commander Islands at Russian contact (Stejneger, 1936, p. 351), then Aleuts probably affected their rapid demise.

More important than initial impact was the continuing interaction between Aleuts and available species for several millennia since. In general, archaeologists consistently see stability and equilibrium in the archaeological record; rapid population decline or expansion of Aleuts (and hence their supportive species) has not been documented. Several conditions relating to populational stability and ecologic adjustment are germane and are outlined below.

1. Resources available during the worst part of the year ultimately regulated population size. The bleakest period was during late winter and early spring when stormy seas prevented Aleuts from hunting and stored food had been depleted

(Veniaminof, 1840, Vol. II, pp. 46-47, 196-197, and 234-235; Jochelson, 1933, p. 11). This is the Aleutian version of Liebig's law of the minimum. Aleuts never devised an effective leveling system to spread the abundance of late spring, summer, and fall throughout the annual cycle. Thus population leveled off, not because marine foods were exhausted but because storage techniques were insufficient and/or weather precluded the normal dependence on hunting and fishing in marine habitats. In other words, confinement to land was very restrictive to a people used to extracting food, mainly sea mammals and fish, from the sea. Population size probably never rose to the point that major staples were being overly taxed.

2. Given the hunting, fishing, and gathering subsistence techniques and their primitive if efficient technology, it would be extremely unlikely that prehistoric Aleuts could have caused drastic reductions in animal or plant resources. Sea mammals from sea otters to whales were abundantly available at Russian contact. There were no pan-Aleutian endangered species until the *promyshlennik* (Russian fur trapper and trader) arrived. Fish and algae were essentially limitless given the technology used to extract them. Perhaps over-indulgence in egg collecting or bird snaring at a colony site or overcollecting sea urchins and shellfish might cause short-term declines in those shore localities, but such fauna would probably rebound rapidly if left alone for several years. Terrestrial plants never figured too importantly in the diet, and only grasses constituted a major raw-material resource. The majority of plants used had leaves, stalks, twigs, or berries removed without disturbing the root structure. Therefore these plants were not removed from their respective plant communities. Only a few plants provided roots (e.g., the Kamchatka lily, *Fritillaria camschatcensis*) for food, and only the collecting of these plants would cause their removal.

3. Aleuts depended heavily on migrating marine species for food and materials. Whales, fur seals, many birds, and salmonids were available in a cyclical fashion and were not year-round residents. Therefore, although migratory sea mammal, fish, and bird populations might be considered finite on an island's shore for any one day, week, or season, a seemingly infinite number of these animals passed through this archipelago filter over the course of a year. Like mainland Eskimos exploiting migratory caribou, Aleuts sampled from a large faunal universe not bound by sharp limits. The Aleut influence on the north Pacific marine fauna was insignificant when compared to European-controlled whaling, other sea mammal hunting, and

fishing, which reached this area during the eighteenth century.*

4. Finally, Aleut population stability was both enhanced and undermined by food sharing as one kind of reciprocity (see, for example, Sahlins, 1972, pp. 215-219 and 235-236). Prior to the late winter food shortage was a period of relative abundance. Winter was the time for large feasts or festivals in which whole villages participated. Other villages from the same or different islands were invited as guests (see, for example, Cox, 1787, pp. 199-201; Veniaminov, 1840, Vol. II, pp. 85-91 and 208). This pattern follows the common Eskimo messenger feasts of mainland Alaska (see, for example, Nelson, 1899, pp. 357-363; Spencer, 1959, pp. 210-228), at which time food consumption and sharing is an important function. It is obvious from the following passage from Veniaminov (1840, Vol. II, pp. 85-86) that such festivals paralleled the Northwest Coast potlatches in their spirit of rivalry:

The formal festivals consisted of scenic stage representations. These were always held in the winter and alternated between one settlement and another. They were organized by the entire population and for them each and every inhabitant gave almost all that he had—*particularly in the way of food supplies*. Thus after each festival everyone of them inevitably went hungry in the full sense of the word. Such a famine was not considered a shameful thing but one of glory. Each settlement, in its turn, sought to outdo each other in the invention of scenes, in the artistry of staging, and in the profusion of their hospitality. (Emphasis added.)

Therefore sharing available food resources in early winter enabled many Aleuts to gain from the accumulations of a few. Hunger and privation, however, were the rewards for feast givers prior to the beginning of the spring food cycle.

*Hett and O'Neill (1974, pp. 37-38) corroborate the limited effects of man on the Aleutian ecosystem through their study of a carbon cycle model: "... the Aleut population played a relatively minor role in maintaining or affecting the stability of the ecosystem as defined by the rate of recovery from disturbance. It should be noted that the Aleut is considered in the context of his natural state where his major effect was as a consumer. These conclusions are quite invalid when applied to civilization's present influence in the subarctic."

Rappaport (1963) notes a similar insignificant effect of native peoples in middle and South Pacific Islands: "On the reef, in the lagoon, and in the sea there continued to be relatively unmodified communities, composed of generally the same elements in generally the same relationships as those that obtained prior to man's arrival. The ecological niche or niches exploited by human populations belonging to such communities depended mainly upon the biotic elements present before the advent of man; the presence, location, and quantity of these elements were subject to little or no control by human beings" (Rappaport, 1963, pp. 166-167).

In sum, prehistoric Aleuts possessed neither domesticated crops nor animals and could only collect food, not produce it. Like other hunters and gatherers, little control could be exerted over potential dietary resources. Over thousands of years of occupation, human population equilibrium was reached on the basis of hunting and gathering. Disequilibrium must have been the exception rather than the norm; as illustrated in Fig. 8, such disequilibrium derived from upsetting either habitat, organisms, extractive techniques, food products, or population or some combination of these. As participants in a generally stable environment, Aleuts were causing few detectable, long-term effects that we can document today. Obviously, by their very presence, Aleuts affected their various habitats and resource organisms on which they depended. However, these effects were indeed minimal when compared to the historic period and the impact that the rifle, motorized boat, and other industrialized technology and exploitation had on that same environment.

CULTURAL PATTERNS AND INTERACTION

Considering the several thousand artifacts collected on Amchitka, the nonarchaeologist might well suppose that we have a firm understanding of ancient Aleut culture. Unfortunately this is not the case. This section begins with a résumé of what little cultural information we actually have. Although this summary applies to the Rat group, our archaeological knowledge of the Near and Andreanof groups is equally scanty if not more so. Only the eastern archipelago has received more intensive investigations (see, for example, Aigner, 1970; Denniston, 1972; McCartney, 1974; Turner and Turner, 1974). Even so, taken as a cultural whole, Aleut prehistory remains poorly known today. This is ironic in light of Dall's having initiated Alaskan archaeology a century ago by excavating along the Aleutian chain.

The state of Rat Island archaeology can be summarized as follows:

1. Only Amchitka has been adequately surveyed for sites; the nine other islands, comprising 67% of the coastline, have not been intensively searched for additional sites.

2. Of known sites, only about 20% have been tested in any fashion; no one site has been extensively excavated with systematic procedures; the largest excavations were those of Hrdlička on Amchitka (Sites 2 and 3) and Little Kiska, but these provided no cultural information besides the artifacts, a few human burials, and a small faunal sample.

3. Only three sites have been radiocarbon dated, and all these are on Amchitka (Sites 31, 32, and 36).

4. Only one house feature has been uncovered (Site 32); other features include several hearths and burials; all features are found in Amchitka sites, and none are known from other islands.

5. Although several human skeletons have been found, these have not been studied as a series nor comparatively reported on in detail.

6. Major Amchitka collections have either gone unanalyzed (Hrdlička and Sense) or have been studied analytically with no comparative syntheses along temporal, spatial, or functional dimensions (Desautels and Cook).

7. Finally, the Rat Island native population was eliminated or removed early during the Russian colonization, and there is very little ethnohistoric literature from which to tie together historic and prehistoric cultures.

Because prehistoric remains (sites, burials, artifacts, faunal debris, etc.) from this island group are generally similar to those found elsewhere in the chain, we view Rat Islanders as taking part in the larger, archipelago-wide cultural milieu. We have adequate evidence that these past peoples adapted similarly to the Aleutian environment. For the above reasons, however, we must often speculate about specific details of the prehistoric past.

Aleutian archaeology may be accurately characterized as becoming more oriented to settlement pattern and to ecologic and systemic approaches over the past decade since these approaches have developed in contemporary archaeology generally (see, for example, Flannery, 1967; Leone, 1972; Redman, 1973). Yet the organization of Aleutian prehistory within these kinds of models is hardly an accomplished fact. Archaeologists working in many other geographic regions have made great strides with these approaches because they operate within a well-blocked-out cultural-historical frame. The major problems of time, space, and function have been addressed, but this cultural-historical foundation is largely lacking in the Aleutians, and we are hindered because of it. Unit concepts (e.g., Willey and Phillips, 1958) have gone undefined and have not been used. For various reasons, namely, poor stratigraphic control in many excavations, few radiocarbon dates, few published reports, and many unstudied museum collections, Aleutian archaeologists have operated largely in a noncomparative manner except at the artifact level. As a result of all these factors, we can offer only a sketchy and speculative synthesis of prehistory for one island group or the entire archipelago.

This section briefly reviews the nature of Rat Island collections and the kinds of interaction that occurred within this island group and between it and neighboring groups.

Rat Island Artifacts

Because the artifacts recovered under AEC-sponsored projects are now stored in the University of Alaska museum and could not be studied easily in preparation for this chapter, no synthesis of the 1968, 1969, and 1971 artifacts is presented here. Instead, the Smithsonian collections of Hrdlička and others were inspected to evaluate artifact variations within the Rat Islands. These artifacts from Amchitka, Kiska, and Little Kiska constitute the largest collections besides those of the AEC.* The Smithsonian collection has never been analyzed and published; only a few specimens appear in Hrdlička's (1945) Aleutian report. Fifty-five of the Amchitka pieces are illustrated in Figs. 9 to 15 of this chapter; all but one of these are from Sites 2 and 3. These show some of the variety of implements and weapons used in procurement and other activities plus the toolmaking skills of ancient Aleuts.

Table 9 summarizes major artifact classes as grouped by activity spheres or use contexts. These classes are taken from reports and collection notes covering all island groups, but those specifically known from the Rat Islands are marked. This listing attempts to organize artifacts of known function; artifacts of unknown function are excluded. In some cases we cannot be certain that an implement was used in only one context. Knives and scrapers, for instance, were probably used in multiple contexts on multiple materials.

It is readily apparent that almost all these typical Aleutian implements are known from the Rat group, indicating strong cultural continuity

*The U. S. Museum of Natural History, Smithsonian Institution, is the repository for a total of 2059 catalogued artifacts from the Rat Islands collected over the past century. A breakdown of this total by island is as follows: Amchitka, 1526 (74%); Little Kiska, 481; Kiska, 34; and Rat, 18. A breakdown by collector is as follows: Hrdlička, 1916 (93%); Guggenheim, 34; Dall, 25; and others, 84. Because of Hrdlička's 1930s field work, the Smithsonian has the largest Rat Island collection with the exception of the recent AEC-sponsored one.

The small Amchitka collection that Guggenheim gave to the Smithsonian has been rather picked over, and few fine pieces are included. It is typical of many collections made by World War II servicemen in that, by the time they became museum acquisitions, mostly broken bits and pieces remained. Hundreds if not thousands of artifacts left Amchitka with World War II military personnel, but very few of these were later donated to museums for safe-keeping. One Amchitka exception is a collection now in the possession of Rockmont College, Denver.

over space. Examples of classes not yet found in the Rat Islands will probably be found in the future. As stressed throughout this chapter, Aleut lifeways are rather similar wherever noted in the chain, and preserved technology is accordingly similar. Differences do occur, however, at the typological or stylistic level beneath that of major classes.

Cultural Interaction Within the Rat Group

Much of the preceding discussion suggests that Rat Islanders interacted in direct proportion to their proximity to one another. Aleuts living closest together would have shared in a greater number of common cultural elements than those living on the most isolated islands. We would expect similarity to be displayed, particularly in artifact assemblages, in that style reflects shared manufacturing norms. On a single island, such as Amchitka, we would expect that two synchronously occupied villages close together would display more common cultural expressions between them than either would to a distant village. Of course, the comparison of assemblages from nearby sites occupied at different periods would indicate nothing about cultural sharing.

It is not possible to test this hypothesis of proximity—similarity on Amchitka by merely reviewing the two AEC artifact reports (Desautels et al., 1971; Cook, Dixon, and Holmes, 1972). A complete study of all the 1968, 1969, and 1971 collections would be required to detect the degree to which proximity and cultural similarity are related. Even then the existing sample may be insufficient, and additional artifact samples may be required to substantiate this postulate. Some of the materials are not comparable temporally. Most of the 1971 artifacts date to about 400 years ago, whereas the 1969 artifacts span a long period, beginning about 2500 years ago.

Furthermore it is not possible to adequately test this proximity—similarity hypothesis between islands because the only sizable non-Amchitkan collection is that from Little Kiska. A demonstration supporting this hypothesis would require additional collections from several different islands.

Cultural Interaction Between Adjacent Island Groups

Comparative Limitations. If comparisons within the Rat Islands are limited, comparisons between major island groups are little better. Limitations in making typological and stylistic comparisons include small sample sizes, noncomparable

sampling techniques, lack of provenience specifications, and lack of typological analyses. These are briefly outlined before offering interim cultural generalizations.

Sample size is critical because, although Rat Island artifacts total about 10,810 (AEC, 8750; Smithsonian, 2060), collections from the Near and Andreanof groups flanking the Rat group total much less. The largest museum collection, to my knowledge, is that of the Smithsonian: Near Islands, 2010 (Attu, 410; Agattu, 1600); Andreanof Islands, 456 (Ilak, 23; Kanaga, 84; Adak, 132; Atka, 105; Amlia, 112). In addition, 936 other Near Island artifacts from Attu, Agattu, and Shemya are treated by McCartney (1971), including those published by Spaulding (1962), Jochelson (1925), and Hurt (1950). Artifacts from any one island, much less any one site, are relatively few in comparison with Amchitka and Little Kiska. Hrdlička's large Agattu collection is the single exception.

More important than mere sample size is the fact that neither Hrdlička nor military personnel responsible for other collections retained all excavated materials. In other words, the collections do not represent the artifact assemblages originally deposited at the sites. Better, complete, and unique artifacts were selected over poor, broken, and redundant ones. Worn and broken flake scrapers and knives, notched stone weights, and fragmented bone and stone implements, for example, were often left in the field. The AEC collections were systematically assembled, with attention paid to all cultural debris. These recent Amchitkan collections are difficult to compare with the older collections from the Near Islands and the Rat Islands (except for Spaulding's Agattu collection) because the analyst never knows what was actually excavated in these adjacent island groups.

Besides making incomplete collections, Hrdlička and military collectors failed to assemble provenience measurements, detailed notes about site context, or relevant maps, drawings, and photographs. We have essentially no information about midden stratigraphy and features or where the collected artifacts originate vertically or horizontally in the midden matrix. Knowing relative artifact positions would make these western island collections much more useful than they are currently.

Finally, no one has classified central or western Aleutian artifacts in either a more traditional typological manner or through cluster analysis of attributes. This condition prevails for the majority of all Aleutian sites. We are thus left with individual artifacts to compare rather than artifact clusters of demonstrated cultural significance.

(Text continues on page 107.)

Fig. 9—Typical Amchitka artifacts (U. S. Museum of Natural History, Sites 2 and 3).

Hunting implements:

- a—g Chipped-stone projectile points or end blades for use in arrows, darts, harpoons, or spearheads such as h—k (basalt and similar stone). (Catalog numbers 396219, 396215, 396289, 396215, 396215, 396289, and 396289.)
- h Bone arrow or dart head with conical tang and slotted tip for a stone projectile point. (Catalog No. 396130.)
- i Bone spearhead with missing tip; the plug tang was inserted into a bone socket piece and probably secured with thong lashing through the basal hole; the original tip was either slotted or had an open basin for a stone projectile point. (Catalog No. 386125.)
- j Bone spearhead with basal lashing lip, slotted tip for a stone projectile point, and an owner's mark incised into one face for identifying sea mammal kills; this head was probably lashed directly to a wooden shaft. (Catalog No. 396138.)
- k Bone spearhead with slotted tip for a stone projectile point and finely incised line decoration; this late style head was embedded directly into a wooden shaft end and lashed around the tang notches; possible use as a fish spear instead of a sea mammal spear. (Catalog No. 387673; this specimen only from Site 20.)

Fig. 10—Typical Amchitka artifacts (U. S. Museum of Natural History, Sites 2 and 3).

Hunting implements:

- a—e Bone dart or harpoon heads; all these heads have wedge-shaped tangs that were held secure in socket pieces such as i and j below. (Catalog numbers 396272, 396127, 396272, 396127, and 396127.)
- f Bone unbarged arrow or dart point with conical tang. (Catalog No. 396142.)
- g—h Bone barbed points with asymmetric tangs; possibly for use on a bird or fish leister. (Catalog numbers 396129 and 396139.)
- i Bone socket piece with peg tang for insertion into a wooden shaft end or into another intermediate bone socket; two wooden inserts in the oval socket end made it possible to wedge a point tang securely between them. (Catalog No. 396287.)
- j Bone socket piece with bifurcated tang; the tang fits directly into a wooden shaft end; wooden inserts were also used in the socket end. (Catalog No. 396151.)

Fishing implements:

- k Bone leister side prong; for use on a bird or fish leister shaft. (Catalog No. 396092.)
- l Cobble sinker or weight with full groove for line or net attachment. (Catalog No. 396191.)

Fig. 11—Typical Amchitka artifacts (U. S. Museum of Natural History, Sites 2 and 3).

Skin-preparation implements:

- a Bone handle for a metal knife blade with step-scarf tang for attachment to a wooden-handle extension; a rusted iron-blade fragment is embedded in the end slot; the side-groove function is unknown. (Catalog No. 396145.)
- b Awl of split proximal end of an albatross humerus. (Catalog No. 396088.)
- c Awl of sharpened proximal end of a bird radius. (Catalog No. 396085.)
- d Chipped-stone scraper blade; hafted for use in wooden handle (dark gray andesitic stone). (Catalog No. 396208.)
- e–g Chipped and partially ground stone ulu blades; probably hafted for use in wooden, bone, or woven-grass handles (argillitic stone). (Catalog numbers 396218, 396334, and 396218.)
- h Small ground stone ulu or knife blade; probably hafted in a wooden handle for use (argillitic stone). (Catalog No. 396218.)

a

e

f

d

g

b

c

h

Fig. 12—Typical Amchitka artifacts (U. S. Museum of Natural History, Sites 2 and 3).

Woodworking implements:

- a Bone adze head; an adze blade such as **b** was lashed into the basin at the upper end, and a wooden handle was lashed onto the longer end by means of the lashing grooves. (Catalog No. 396288.)
- b Chipped and partially ground stone adze blade (dark gray hard stone). (Catalog No. 396210.)
- c Bone wedge with holes resulting from using the wedge as an upper bearing or holder for a bow drill. (Catalog No. 396220.)
- d Small peg-like bone wedge. (Catalog No. 396219.)
- e Scoria abrader. (Catalog No. 396306.)
- f Chipped-stone scraper; the angled steep edge is unifacially flaked. The scraper is hafted to a wooden handle for use (basalt). (Catalog No. 396292.)
- g Chipped-stone drill bit; the bit is hafted to a drill shaft for use (dark brown hard stone). (Catalog No. 396293.)
- h Flake drill (gray andesitic stone). (Catalog No. 396340.)

Fig. 13—Typical Amchitka artifacts (U. S. Museum of Natural History, Sites 2 and 3).

Household implements:

- a—b** Bifacially chipped knife blades; used hafted or unhafted (basalt and gray andesitic stone). (Catalog numbers 396213 and 396214.)
- c** Bifacially chipped knife blade with tang notches for lashing to a wooden handle (basalt). (Catalog No. 396290.)
- d** Bifacially chipped asymmetric knife blade with one tang notch for lashing to a wooden handle (basalt). (Catalog No. 396291.)
- e** Bifacially chipped knife blade; probably hafted in a wooden handle before use (basalt). (Catalog No. 396290.)
- f** Flake knife or scraper with unifacial chipping along both cutting edges (obsidian). (Catalog No. 396296.)

Fig. 14—Typical Amchitka artifacts (U. S. Museum of Natural History, Sites 2 and 3).

Household implements:

- a** Carved stone lamp with charred oil residue. (Catalog No. 396186.)
- b** Combination hammerstone and grinder; both ends have been used for pounding and two side facets have been worked flat by grinding. (Catalog No. 369307.)
- c** Combination hammerstone and grinder; the edges and particularly the ends have served as pounding surfaces; a flat grinding facet is worn on one face. (Catalog No. 369197.)

Fig. 15—Typical Amchitka artifacts (U. S. Museum of Natural History, Sites 2 and 3).

Collecting implements:

- a Ivory digger with carved handle and incised line decoration. (Catalog No. 396242.)
- b Bone probe or digger with decorative end carving. (Catalog No. 396163.)

Articles of adornment/miscellaneous:

- c Ivory/tooth labret. (Catalog No. 369100.)
- d Ivory/tooth labret. (Catalog No. 396097.)
- e Bone labret. (Catalog No. 396107.)
- f Bone bead. (Catalog No. 396115.)
- g Bone “gauge”; use unknown; surface polish is often found on these pieces at the ends below the pips. (Catalog No. 396112.)

Table 9—Aleutian Artifact Inventory

Contextual category	Artifact class	Figure
Hunting implements	Bone harpoon heads (detachable)*	10(a–e)
	Bone spear/lance heads (nondetachable)*	9(i–k)
	Bone dart heads*	
	Bone arrowheads*	9(h)
	Bone bird blunts*	
	Bone loose shafts*	
	Bone socket pieces/foreshafts*	10(i,j)
	Stone projectile points/end blades*	9(a–g)
	Wooden covers for stone end blades	
	Wooden shafts for harpoon/spears/darts*	
	Bone bladder nozzles	
	Bone and wooden clubs*	
	Bone bird gorges	
	Bola stones (?)*	
Fishing implements	Bone fishhooks*	
	Bone fish leister points/side prongs*	10(g, h, k)
Collecting implements	Stone weights/sinkers*	10(l)
	Bone diggers/probes*	15(a, b)
	Bone mattock and pick heads*	
	Net and basket containers	
Woodworking and boneworking implements	Stone maul heads*	
	Hand hammer stones*	14(b)
	Bone wedges*	12(c, d)
	Bone adze heads*	12(a)
	Stone adze blades*	12(b)
	Bone drill bearings*	12(c)
	Stone drill bits*	12(g, h)
	Stone scraper blades*	11(d), 12(f)
	Stone flake scrapers*	
	Bone knife handles*	
	Stone knife blades*	13(a–e)
	Iron knife blades*	11(a)
	Scoria/pumice abraders*	12(e)
	Whetstones*	
Stoneworking implements	Bone flaking tools	
	Bone ulu handles	
	Stone ulu blades*	11(e–h)
	Stone scraper blades*	11(d)
	Stone flake scrapers*	13(f)
	Iron knife blades*	11(a)
	Bone scrapers	
	Bone cutting/trimming tablets*	
	Bone awls/punches*	11(b, c)
	Bone needles*	
Household implements	Bone needle cases	
	Bone ulu handles	
	Stone ulu blades*	11(e–h)
	Stone knife blades*	13(a–e)
	Bone fire drill bearings*	12(c)
	Wooden fire drill base	
	Sulfur (for fire starting)	
	Hand hammer stones*	14(b)
	Ocher grinding slabs/stones*	14(c)
	Stone lamps*	14(a)
	Stone griddles	
	Stone bowls	
	Bone bowls/containers	
	Bone container sides*	
Articles of adornment and decoration	Wooden bowls/trays	
	Bone and wooden spoons/scoops/shovels	
	Bone/tooth labrets*	15(c–e)
	Bone/tooth spools*	
	Bone/tooth pins	
	Bone/tooth pendants	

Table 9—(Continued)

Contextual category	Artifact class	Figure
	Pendants made of drilled or grooved mammal teeth*	15(f)
	Bone beads*	
	Shell beads/pendants*	
	Bone chains	
	Bone/tooth animal and human figurines*	
	Bone combs	
	Bone and wooden masks	

*Known from Rat Island collections.

As with the intragroup comparisons above, artifact or cultural similarity between island groups directly expresses contact between Aleuts of these groups. Although not all contact need imply cultural transmission, stylistic similarity may be explained realistically by such transmission.

Intergroup Comparisons. I suggested several years ago (McCartney, 1971) that distinctive characteristics of Near Island material culture ultimately derived from the relative isolation of that group from the rest of the archipelago. After I completed that article, the Desautels et al. (1971) monograph appeared, and I commented that this report suggested that Amchitka was more closely related to central and eastern assemblages than to those of the far western islands (McCartney, 1971, p. 106, postscript). Since I have studied additional Rat and Andreanof artifacts, a general updating of the 1971 conclusions is in order. But the comparisons are now in two directions rather than one, as was the case with the Near Islands at the chain's end.

What can we hope to learn from artifact distribution studies? In regard to the ecologic, systemic study of marine subsistence emphasized above, we should ascertain if, in fact, all islanders adapted similarly. Even casual study shows us that indeed all these various island collections display the same artifact core as is listed, for instance, in Table 9. At the stylistic level, however, we are primarily concerned with ascertaining cultural spread over time and space. As mentioned previously, most areas of North America have a cultural-historical framework established through past decades of archaeological study. The Aleutians lack any such framework. Therefore, seeking evidence of cultural flow—population contact along this attenuated island chain requires distributional input about the spread of cultural characteristics. We have postulated that distance between islands and island groups is inversely proportional to cultural contact and spread. To establish such a relationship requires that we demonstrate some

evidence of contact and cultural flow. Our medium is artifacts and other physical manifestations of cultural patterning. The physical anthropologist would test such contact by studying gene flow expressed in human skeletal series. A linguist would try to establish continuity and discontinuity on the basis of present Aleut speakers and historic language documents. Distributional artifact studies, in and of themselves, may seem a bit humdrum; yet results of these comparisons directly indicate adaptations, population movement, in situ development, trade, or other interaction and adjustment. The critical questions revolve around why these distributions are what they are. What cultural and social regularities, in other words, are being demonstrated by particular artifact clusterings in space? Although the explanatory phase will benefit greatly from accurate distributional descriptions based on large-scale comparative studies, an attempt is made in a later section to find ethno-historic reasons for stylistic spread.

Long artifact attribute and type lists will not be included in this chapter. My previous listing of shared pan-Aleutian traits (McCartney, 1971, pp. 138-139, Table IV) stands as presented. These 32 items are indicative of artifacts found throughout the chain, and more will certainly be added in the future. The listing of central and eastern Aleutian artifacts (McCartney, 1971, p. 141, Table V) also remains generally accurate, with many Rat Island examples now added that demonstrate the western distribution of most of these 25 items to that island group. Conversely, Near Island characteristics (McCartney, 1971, p. 136, Table III) have been significantly altered. At least nine of the original 29 items are now known from the Rat Islands as well, but these may be restricted to these two groups only. We could add several artifacts whose distribution is currently limited to the Rat group. These would include iron-bladed knives (Desautels et al., 1971, p. 246, Fig. 124) and conical-tanged arrow points (Desautels et al., 1971, p. 197, Fig. 92 a and b; Cook, Dixon, and Holmes, 1972, plate 16).

As a result of further research since 1971, I now offer a subjective but considered opinion that there is far more continuity throughout the chain than discontinuity and that the Near Island group is probably not as different or distinctive from the remaining groups as previously suggested. As more is learned about artifact variation and spread from newly excavated as well as existing museum collections, it appears that every major island group will have distinctive implement styles not found elsewhere and at the same time will share artifacts with one or more other adjacent groups. Without a complete analysis of all available artifacts, one may intentionally or unintentionally stress continuity by listing shared traits or discontinuity by listing distinctive traits. A further complication is lack of time control to judge contemporaneity; the large majority of extant Aleutian artifacts are not accurately dated.

The following nine hypotheses summarize our current interpretation of artifact distribution; all demand rigorous examination in the future:

1. All island groups have been in more or less continuous contact for at least the past 2500 to 4000+ years; no group has remained isolated for a period sufficient to produce high-level artifact dissimilarity.

2. Standardization of artifact form and style is due in part to common environmental adaptation throughout the chain. Continuity over time and space is due to a relatively stable environment for approximately 4000+ years; readaptations to subsistence alternatives were not required which would be reflected in subsistence technology and artifact inventory.

3. Cultural interaction and population contact was heightened by geographic restrictions on travel; homogeneity resulted from east-west travel only along the chain with no interior to occupy via river systems as in mainland Alaska.

4. Artifacts appear to have been spread independently of one another; no large clustering appears to occupy the same space simultaneously. This conclusion may, however, be based on incomplete knowledge of actual cluster spread. A small complex of late prehistoric artifacts previously described (McCartney, 1971, p. 96) may exemplify implement styles spreading to varying degrees through the chain. Whether artifacts spread singly or in clusters, the critical questions are what functional, adaptive, or other cultural processes were responsible.

5. Material specificity is an important factor in artifact commonality. For technologic reasons, one material may be better suited for a particular artifact than some other. This is not unique to the Aleutians, but the particular combination of mate-

rials to choose from may be. Examples of material-tool associations are as follows: slate or argillite (soft, fine grain), ulu blades; basalt (hard, brittle), knife and scraper blades and projectile points; welded tuffs (soft, vesicular), carved bowls and lamps; and scoria and pumice (soft to hard, vesicular), abraders. Only rarely is one material substituted for another, which causes a given material's properties to be disregarded. Much less frequently, form rather than material dictates persistent use. Drilled sea-mammal teeth with no other alteration are commonly used for pendants or beads, or bird-wing bones are usually sharpened at one end to make awls and punches.

6. Artifactual distribution carries no assumed implications about spread of physical type (Paleo-Aleuts or Neo-Aleuts) or language dialects (eastern, central, or western). The entire chain, plus the adjoining Alaska Peninsula, is a geographic continuum along which race, language, and culture assorted themselves independently since their modes of transmission are distinct (McCartney, 1974).

7. On the basis of proximity, the Rat Islanders had more contact with adjacent Near and Andreanof (including Delarof) people than with any other group. Because the Delarof Islands and Buldir Island are intermediate between the Andreanof and Near groups, respectively, and because these islands probably either supported no resident villages (Buldir) or only a few (Delarofs), these islands would likely be peripheral hunting, fishing, and collecting areas for the remaining Rat Islanders. Recent Delarof estimates show a combined colony bird total of 250,000 and a sea lion total of 6,600 (Sekora, 1973); these compare favorably with abundance figures for Buldir and the remaining Rat Islands.

8. Because the Aleutian chain extends from the mainland far into the North Pacific, the western islands, including the Rat group, will tend to show less cultural interaction with mainland Alaska than the closer eastern islands. A firm demonstration of this awaits additional study of central and western Aleutian artifact collections.

9. Finally, trade or exchange was not conducted at the pan-Aleutian level. Rather, what little evidence we have suggests trade predominantly within island groups (compare Lantis, 1970, p. 274, for supporting ethnographic data). Part of the problem lies in establishing sources of land-bound materials that, because of their scarcity, would lend themselves to trade. Obsidian is an excellent choice. Because it is hard, brittle, and has conchoidal fracture, it is an excellent material for projectile points or knife and scraper blades, but obsidian was not widely traded throughout the

chain. Of all the Near Island specimens examined, none are of obsidian (McCartney, 1971, p. 136, Table III). The Rat group collections (AEC and Smithsonian) reveal only two pieces, one of which is illustrated in Fig. 13f of this chapter (Turner, 1970, p. 121; Desautels et al., 1971, pp. 78 and 109; Cook, Dixon, and Holmes, 1972, p. 23). I have located only one obsidian artifact in the Smithsonian Andreanof collections. In the eastern Fox Islands, however, where at least three or four obsidian sources are reported (Umnak, Unalaska, and Akutan; Elliott, 1886, p. 148; Hrdlička, 1945, pp. 98-99), obsidian is not at all rare. It makes up, for instance, about 15% of the 8000-year-old Anangula core and blade complex (McCartney and Laughlin, 1964), 5 to 48% of Chaluka (Umnak) artifacts (Denniston, 1966, p. 91, Fig. 3), 4.5% of Akun waste flakes (Turner and Turner, 1974, p. 47, Table 3), and 5.4% of Izembek flakes (tip of the Alaska Peninsula; McCartney, 1974, p. 72). The highest use of obsidian reported is at the Ashishik Point site (northeastern Umnak), which is very close to the obsidian source on that same island end (Denniston, 1972, pp. 94-95 and 296, Fig. 17). Obsidian here ranged between 40 and 90% in different levels. These indications of distribution suggest that obsidian was quarried only in the Fox Islands and that there was hardly large-scale trafficking of this material throughout the chain. The two Rat pieces must have passed from east to west by undirected exchange.

The Rat Islanders exploited one regional resource apparently found in few other localities. This is pre-eighteenth-century foreign iron, and it, too, failed to be traded widely to other areas. Desautels et al. (1971, pp. 243-248) found 12 iron-bladed knives at Sites 10, 14, 35, and 36, and Cook, Dixon, and Holmes (1972, p. 21, plate 24) found two pieces at Site 32. Hrdlička's Smithsonian collections include seven iron-bladed knives or iron-stained bone handles (Amchitka, four, including the one shown in Fig. 11a; Little Kiska, two; and Kiska, one). Because none of these were associated with Russian- or American-period trade goods and clearly are not just surface finds, we may safely take them to be precontact in age. The fact that all the blades are hafted in typical Aleut style bone handles rather than having originally manufactured handles suggests that the iron alone was acquired from an Asiatic source and made into knives once in the hands of Aleuts. The ultimate source of iron prehistorically was China or Japan; it was obtained by the Aleuts from boats wrecked on Aleutian shores. There is little support for Jochelson's (1933, p. 22) hypothesis of Chukchi-Eskimo-Aleut distribution. Several references to

early iron and copper suggest fairly wide distribution at the early contact period. Steller reported iron knives in the Shumagins in 1741, shipwrecks were noted on Kodiak, Atka, and in the western islands, and iron exchange between Aleuts and Asiatics or Europeans is referred to on Avatanak (east of Unalaska) and Attu (Coxe, 1787, p. 50; Jochelson, 1933, pp. 21-23; Hrdlička, 1945, pp. 100-101; deLaguna, 1956, pp. 62-63). Iron from Kodiak or the Alaska Peninsula shores was traded to the eastern Fox Islands (Hrdlička, 1945, p. 142).

Archaeologically we do not find prehistoric evidence of wide metal use in the chain. Of all the prehistoric collections I have studied or have knowledge of, I have never found metal fragments or bone knife handles with iron or copper oxidation stain except in the Rat group. The Smithsonian has one bone knife handle from Amaknak (Fox Islands) that is similar to, but not exactly like, those found in the Rat Islands, but the piece has no metal stain in the blade slot. Presumably relatively rare shipwrecks during the late prehistoric era supplied the iron for the Rat Islanders since no terrestrial or meteoric sources are known in the Aleutian chain. Shipwrecks would be expected to occur with greater frequency the more recent the period.

Obsidian and iron, then, are examples of two scarce but useful commodities that might have been exchanged widely. Of course, iron may have been even more limited and insufficiently abundant for trade. The fact that long-distance trade networks did not develop may have been due to the fact that material such as obsidian and iron was not required for successful toolmaking and survival. They were luxuries to be used if available. They seem to substantiate the hypothesis that ideas of style spread widely but materials spread only regionally.

Other precious materials traded include dentilium, amber, mineral pigments, and porphyry (Veniaminov, 1840, Vol. II, pp. 94-95; Lantis, 1970, p. 275).

Explanation of Artifact Similarity. It is appropriate to suggest possible mechanisms responsible for the spread of artifact styles. Although we have stressed Aleut seasonal movement as an adaptive mechanism, little has been said thus far about social interaction and movement. Given that interaction is expressed archaeologically in shared artifact styles, then how did short-term social interaction facilitate the sharing of normative patterns? Two major ways of interacting are immediately apparent. One is that resulting in finished artifacts being exchanged between dif-

ferent villages, islands, or island groups. Second, movement of people rather than items will spread styles even more effectively than exchange.

Trade and festivals are two previously mentioned modes of social interaction between Aleuts of different villages. In fact, festivals were likely the most important occasions for social as well as material exchange. Gifts, or more realistically investments of presents demanding reciprocity, were given during the winter festivals or feasts (Veniaminof, 1840, Vol. II, p. 91). Such artifact scattering contributed toward homogenization of styles within an island group at least. Short-range trade of weapons, masks, clothing, skins, etc., also occurred between villages in other trading situations (Coxe, 1787, p. 197; Veniaminof, 1840, Vol. II, pp. 110-111). As pointed out above, long-range trade throughout the chain is not borne out by archaeological evidence or by ethnohistoric accounts.

Perhaps more important than the movement of items was the movement of people, either temporarily or permanently, from one residential alliance to another. There is abundant ethnohistoric information about both males and females changing their residence willingly or unwillingly. For instance, men moved for a year or two to their wife's village at marriage to perform bride service. Matrilineal clans appear to have established kin, and clan exogamy would likely have a man marrying his mother's brother's daughter, a member of another matriclan. Or, if he did not marry his cousin, a man would likely marry another nonclan woman from another village to expand political bonds to that village. Besides, in small villages of related families, it might be difficult to find the proper spouse within the village at marrying time. Because residence after marriage was at the original village of the husband (patrilocal), the wife would be moving into a new community. Boys were preferably instructed during adolescence by their maternal uncles (avunculate), and this would usually occur at the mother's original village prior to marriage. When we add warfare captives or slaves to the above, we obviously find significant social movement (for details of kinship, marriage, education, and warfare, see Veniaminof, 1840, Vol. II, pp. 73-108; Lantis, 1970, pp. 205-271).

Because people will express learned styles when manufacturing implements and other material goods, reshuffling Aleuts from village to village and even from island group to island group resulted in spreading stylistic behavior. However, since Aleut men are believed to be the makers of more durable artifacts (bone, tooth, stone, and wood) than those made by women (grass, skin, gut, hair, etc.), our

archaeological collections primarily express spread of male cultural behavior.

CONCLUSIONS

This chapter relates to Aleutian archaeology of the past, present, and future. Archaeology over the past century has largely been eastern-oriented, artifact-centered, nonclassificatory, and non-comparative. It quite logically has treated origins and development as central issues. Integration of ethnohistoric and archaeological data has profitably stressed temporal continuity out of the distant past. But, as one part of Alaska most intensively occupied and dominated by Russian and later American trading companies, the Aleutians have never been studied commensurate with their historic importance.

This chapter centers on the Near and Rat Islands, especially on Amchitka. Archaeological data from that island provide a much needed western counterpoint to eastern-island information to reveal what is culturally representative of the entire chain. Artifacts have been given only secondary consideration here because most of them have been adequately treated in previous publications. Another reason is because archaeologists today are looking beyond artifacts at less tangible, but no less real, cultural phenomena. By stressing the spatial dimension, one immediately becomes engrossed with such interrelated cultural aspects as settlement patterns, subsistence, demography, social organization, trade, and religion as well as technology. We are pressing for cultural dynamics that operated within the Rat Islands to understand the relative importance of determinants as described above.

Future Aleutian archaeology will progress the furthest by addressing hypotheses such as those set forth in this chapter. Amassing more artifacts will not, in and of itself, answer the sorts of human behavior questions raised here. Salvaging prehistoric remains from endangerment by man or from natural erosion is important, but it will be more fruitful to an understanding of Aleutian prehistory if our excavations also aim at higher level questions, as, for instance, those dealing with adaptation, interaction, and development.

Future archaeological research will continue the interdisciplinary approach exemplified by the AEC ecologic studies on Amchitka. The kinds of questions now raised cannot be adequately answered without input from other scientists of the physical and biological environment and integration of their information.

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History, 1741-1967

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Amchitka has long been subject to man's influence. When discovered by the Russians in 1741, the Aleutians had 10,000 to 20,000 inhabitants and Amchitka itself perhaps 100. Hard treatment caused their number to fall drastically, and by 1849 Amchitka was abandoned. No one has lived there on a permanent basis since, but old living sites are still visible around the edges of the island.

Pressure by Russian and American hunters led to the near extermination of sea otters, conservation measures not having been kept up after the 1867 purchase; the 1911 Fur Seal Treaty, however, served also to protect sea otters, and they have recovered well. In 1913 the Aleutians were set aside as what is now called the Aleutian Islands National Wildlife Refuge.

In 1921 blue foxes were introduced onto Amchitka for support of Aleuts from Atka. As a result the Aleutian

Canada Goose was extirpated from the island. The foxes themselves were finally eradicated from the island by 1960 by an extensive poisoning program.

During World War II Amchitka became the forward fighter-bomber base in the campaign against Japanese-held Attu and Kiska. About 5000 troops were present on the island then, and facilities were later added to house an authorized troop strength of about 16,000. Many structures, roads, three airstrips, and much miscellaneous debris remain from the war years.

In 1965, 1969, and 1971, nuclear shots were fired underground at Amchitka by the U. S. Department of Defense and the U. S. Atomic Energy Commission. During the first of these, there was a small bioenvironmental program, and, during the last two, a large one, the results of which are reported in other chapters of this book.

No one knows when man first set foot on Amchitka. It is believed that Paleo-Aleuts came to Amchitka from the east at least 2500 years ago as part of their slow clockwise advance around the shores of the Bering Sea. Thereafter for centuries these people lived on these islands and called them home, drawing their living from the rich seas about. Their origins faded into myth. Their arts of life changed little over the centuries. They exploited the resources of the area as far as their numbers and their skills let them, leaving to this day signs of their presence in numerous living sites around the edges of this and other islands marked by lush green growth and by sprinklings of shell and bone fragments on the beaches below some of these sites as the sea cuts into the cliffs supporting them.

THE RUSSIAN DISCOVERY

It is even uncertain when Amchitka was first seen by western man and thus entered into the light of written history. The Russian Sokolov (1851, quoted in Golder, 1922, Vol. I, p. 199) believed that Amchitka was the island sighted by the crew of Bering's ship the *St. Peter* on Sept. 25,

1741 (Old Style*), and named by them St. Markiana. Golder disagreed; he believed it was Kiska that was sighted that day. But it does not matter; if Amchitka was not seen in 1741, it was within the next two decades.

Bering's ship came to an end on Bering Island, of the Komandorskie Islands, after months of beating westward against hostile winds. Bering himself died a month and a day later, and the surviving members of the expedition spent the winter in horrible circumstances. They ate what they could find (foxes, sea otters, seals, and sea cows), and, when those who survived recovered their strength, they broke up the first *St. Peter* and built another smaller ship and went home. Only 45 of the original 76 men on the *St. Peter* survived scurvy and the hardships of winter to return at last to Petropavlovsk in Avacha Bay, Kamchatka, in August 1742 (Golder, 1922, pp. 235, 281-282).

Among the things the returning crew brought back with them were some of the skins of the foxes, fur seals, and sea otters they had subsisted

*Russian dates of that period were by the Julian calendar. September 25 is equivalent to October 6 by the Gregorian calendar now in use.

on during the winter. This raised much excitement. The Russian spread across Siberia had been a tumultuous rush by small groups of men looking for sources of furs not yet exhausted by overhunt and overkill. So impetuous was this rush that it had taken only 58 years, from 1581 to 1639, to advance from the Urals to the Pacific at Okhotsk, a distance of nearly 5000 km. And here now was promise of more furs to the east. They were across water to be sure, but those unknown or uncomprehended risks were more than balanced by the promise of riches for the taking.

It fell to a local entrepreneur, Basov, to outfit the first commercial venture east in 1743 and then again in 1745, 1747, and 1749. After that the record becomes very confused as to who went when, in what ships, and if they returned with how many furs. In 1823 Vasilii Berkh tried to reconstruct the history but was only partially successful. Makarova (1975, pp. 37-78, 117-139, 209-216), who has access to what remains of Berkh's sources and to others in the U.S.S.R. Central State Archives of Ancient Acts, reports that there were 22 expeditions to the east between 1743 and 1755, 48 more by 1780, and 22 more by 1800, by which time exploitation was regularized by the Tsar giving a monopoly to the Russian-American Company.

The records are vague about individual islands, leaving it uncertain which adventurer was first on Amchitka. Basov's trips were to the Komandorskie Islands only. In 1745 Nevodchikov wintered on Attu and Agattu, which are to the west of Amchitka. Probably Amchitka was discovered by Bashmakov, either on his 1753-1755 trip on the *Ieremiia* (Jeremiah) or on his 1756-1758 trip in the *Petr i Pavel* (St. Peter and St. Paul). On the first of these trips, he was wrecked on Adak, which is to the east of Amchitka, after having discovered eight islands. On the second of these trips, it is noted that he stopped at "the fifth from the Near Islands" (Makarova, 1975, p. 51). This may have been Amchitka itself. The earliest specific reference to Amchitka I have found is Makarova's note (1975, pp. 61, 211) that Vorob'ev's ship, the *Ioann Ustiuzhskii*, touched at Amchitka and others of the Rat Islands on a trip from 1760 to 1763.

RUSSIAN EXPLOITATION

The Russian promyshlenniki (hunters) found the Aleutian Islands inhabited by a people they came to call Aleuts, perhaps 15,000 of them. The Aleuts were people well adapted to the islands they lived among but not to encounter with these strangers from the west. They were a stocky

well-built people with facial tatoos and wearing lip labrets and bones through their noses. They were inured to what we call hardships, often going barefoot and usually eating their fish raw. All the early observers remark on the Aleuts' skill with baidarkas (what we now call kayaks). No European not trained from youth could handle a baidarka like an Aleut; in later years after the Aleuts were thoroughly subdued, this skill made the Aleuts the most valued of the Russian-American Company's native assistants.

Early contacts were far from smooth and amicable. There is evidence that the Aleuts had a tradition of hospitality to strangers (Veniaminov, 1840, Vol. II, p. 57; Lantis, 1970, pp. 191-192), but the crude Russian promyshlennik did not appreciate this aspect of the savage before him. To the promyshlennik the Aleut was an expendable hunter he could use to extend his own efforts in harvesting the riches all about. The promyshlenniki drove themselves; they drove these new servants even harder. There are numerous well-documented stories of abuse of the natives, such as the story of Soloviev tying a group of men together and firing his rifle at them to see how many the bullet would go through before stopping; it stopped in the ninth man (Veniaminov, 1840, Vol. II, p. 189; Bancroft, 1886, fn. pp. 151-152).^{*} The natives retaliated, the Russians called it murder, and the result was near genocide.

A large fraction of the Aleut population disappeared in the first hundred years of Russian occupation. Estimates of their original numbers vary; Lantis (1970, pp. 172-179) thinks 12,000, Veniaminov (1840, Vol. II, p. 177) thought 12,000 to 15,000, Quimby (1944, p. 3) says 16,000, Laughlin (1967, p. 427) suggests over 16,000, and Bank (1958, p. 113) thinks 20,000. When systematic and accurate censuses began in 1830, there were about 7000 Aleuts and Koniags,[†] and, after the epidemics[‡] of the late 1830s, about 4000

^{*}The reader is cautioned against excessive reliance on Bancroft. Ivan Petroff's translations and research for Bancroft formed the evidential basis of Bancroft's history, and Petroff wrote some of it. He was not always reliable and was, in fact, later proved capable of deliberate falsification. Although no one has done a point-by-point check, his record and reputation throw a shadow over the trustworthiness of Bancroft's book and over Petroff's other works on Alaska as well, including his contribution to the 1880 census (Petroff, 1884). The last solid word on Petroff's career is Pierce (1968).

[†]The Koniags were really Kodiak Eskimos, but the Russians considered them Aleuts and counted them thus in censuses.

[‡]Veniaminov (1840, Vol. II, pp. 178, 197-199) mentions "an epidemic of coughs with pain in the chest" in 1830 and 1831 and smallpox from 1829 to 1838.

(Table 1). As the mention of epidemics indicates, it was not only direct killing that reduced their numbers. The earlier promyshlenniki took hostages of children or women and sent the men out to hunt with a quota of furs to be met to recover their families. Later, men were conscripted to move along with the hunters and work for them with no assurance and little likelihood of ever returning. The intervention of the Russian government did decrease the severity of this treatment but left forced labor as a regular practice. One must remember that during this period serfdom still existed in Mother Russia; that institution was never brought to Russian America. However, there remained such incidents as the time in 1800 when Baranov sent a fleet of 300 men in baidarkas back to Kodiak after having established Fort St. Michael near present-day Sitka. En route at Peril Straits 200 of them died from eating poisonous mussels (Bancroft, 1886, p. 390; Chevigny, 1942, p. 171). As an old Russian saying puts it, "God is high above and the Tsar far away."

There is no need to detail the development of Russian America here. The western Aleutians were quickly passed by. The principal settlements were Kodiak and then Novoarkhangelsk (Sitka). Order was brought to Russian America, first by monopoly given to the Company in 1799 and then by the practice of assigning naval officers to 5-year terms as governors of the Company.

A number of scientific and supply expeditions were sent out. The last two sent by the Siberian route were those of Krenitsyn (1764–1771), which was singularly unsuccessful because of repeated shipwrecks, and of Billings (1785–1793), who had previously served under the famous Englishman Captain Cook. Billings made one trip north down the Kolyma River to the Arctic Ocean in 1787 and two trips to Alaska from Pacific ports sailing in 1788 and 1791 and reaching as far east as Prince William Sound. Technically his information had little value because it repeated ground that Cook had covered in 1778 (and published), but Billings' reports did make known to the Russian government the abuses of the Aleut natives being perpetrated by the promyshlenniki. The first completely seaborne expedition was that of Krusenstern and Lisianskii (1803–1806). Their ships were also the first Russian ships to go around the world. This expedition is most notable for the help that Lisianskii, in the ship *Neva*, was able to give to Baranov in recovering Sitka from the hostile Tlingits after the massacre of 1802. Thereafter numerous names occur, Golovnin, Hagemeister, Kotzebue, and Lazaref, few of whom paid any attention to the western Aleutians.

The Church came to Alaska in 1794, at first ineffectively, but eventually she supplied the only Orthodox saint ever to come out of North America (St. Herman, 1757–1837, canonized in 1970) and the great Ivan Veniaminov. Veniaminov was at Unalaska from 1824 to 1834 and at Sitka until 1838. A powerful man physically, a gifted linguist, and a keen observer as well as a strong man of God, he is one of our primary sources of objective knowledge of the Aleut and his ways, albeit as altered by 80 years of Russian dominance. His abilities eventually made him Innokentii, Metropolitan of Moscow and head of his church (Bensin, 1967; Hulley, 1970, pp. 166–167).

Gradually the population of the western Aleutians decreased. I can find population figures for Attu and Atka over the longest period of time but only occasional mention of other places (Table 2). Fluctuations in population are due in part to the fact that the Russian administration moved people around freely. In 1821 the Atka District* was reorganized, and the people of the west concentrated in fewer centers. Atka got a permanent Russian settlement of about 50 Russian hunters and 60 Aleuts and with a church housing the Administration (!) and the priest. The Amchitkans and other Rat Islanders were brought eastward, some to Adak and some to Korovin Bay on the north side of Atka. A snow avalanche at the latter place buried the village and killed its inhabitants. The Adak group of Amchitkans was later moved to Atka where descendants of the tribe were still said to have been living at the beginning of this century, so at least went the oral tradition in 1952 (Bergsland, 1959, pp. 13–14, 68–69). In a conflicting account, Dall, writing closer to the event in 1877, reported that the last permanent settlement on Amchitka was abandoned in 1849 (Dall, 1877, p. 44). Thereafter, after over 2500 years of human occupation, Amchitka had no permanent residents. The village sites remain, and today we see them as areas of lush greenness with high tangles of the grass *Elymus* and prominent stalks of cow parsnip, *Heracleum*.

One might wonder how it is that Atka rather than Adak or Amchitka became the administrative center of the western Aleutians. Jones (1960, p. 5) thinks that "the Russians with their sailing ships did not care for [Amchitka] because of its very poor harbor and reefy coast. This view seems to be supported by the fact of the survival here of the largest remnants of the sea otter populations." Indeed the navigational guide of 1886 says that

*Consisting of all the western Aleutian Islands, the Komandorskie Islands, and, for a while, the Kurile Islands.

Table 1—Population of Russian America and Alaska

Year*	Total	Aleuts†	Russians‡	Creoles§	Year*	Total	Aleuts†	Russians‡	Creoles§																																																																						
1741		12,000			1849	8,892	4,322	469	1,562																																																																						
1799	8,200		225		1850	9,091	4,084	485	1,636																																																																						
1805			470		1851	9,273	4,041	505	1,703																																																																						
1806		5,234			1852	9,452¶	4,187	567	1,693																																																																						
1817			421		1853	9,578**	4,298	592	1,687																																																																						
1818	9,101	3,252	375	280¶	1854	9,514¶	4,259	547	1,751																																																																						
1819	9,019		391	244	1856	9,725	4,127	658	1,902																																																																						
1821		4,880	526	130	1857	9,788**	4,541	640	1,903																																																																						
1822	8,286	5,334	488	553	1858	10,065¶,**	4,553	754	1,838																																																																						
1824	9,636		488	548	1859	9,992¶,**	4,454	615	1,910																																																																						
1827	10,561		734	1,295	1860	10,540**	4,592	595	1,909																																																																						
1830	10,327¶	6,864	531	916	1862	10,156¶	4,752	577	1,892																																																																						
1831	10,453**	6,917	572	949	1863	10,124¶,**	4,712	632¶	1,989¶																																																																						
1832	10,493	6,949	587	935	<table> <tr> <th colspan="5" rowspan="13">Aleutian Islands Census District</th><th>Year</th><th>Total</th><th>Aleuts</th><th>White men</th><th>Creoles</th></tr> <tr> <td>1867</td><td></td><td></td><td>812</td><td></td></tr> <tr> <td>1870</td><td>28,747</td><td></td><td>483</td><td>1,421</td></tr> <tr> <td>1880</td><td>33,426</td><td>2,451</td><td>430</td><td>1,756</td></tr> <tr> <td>1890</td><td>32,052</td><td>2,361</td><td>4,298</td><td></td></tr> <tr> <td>1900</td><td>63,592</td><td></td><td>30,493</td><td></td></tr> <tr> <td>1910</td><td>64,356</td><td>1,083</td><td>36,400</td><td></td></tr> <tr> <td>1920</td><td>55,036</td><td>1,080</td><td>27,883</td><td></td></tr> <tr> <td>1929</td><td>59,278</td><td>1,116</td><td>28,640</td><td></td></tr> <tr> <td>1939</td><td>72,524</td><td>1,298</td><td>39,170</td><td></td></tr> <tr> <td>1950</td><td>128,643</td><td>5,600</td><td>92,808</td><td></td></tr> <tr> <td>1960</td><td>226,167</td><td>6,011</td><td>174,546</td><td></td></tr> <tr> <td>1970</td><td>302,173</td><td>8,057</td><td></td><td></td></tr> </table>					Aleutian Islands Census District					Year	Total	Aleuts	White men	Creoles	1867			812		1870	28,747		483	1,421	1880	33,426	2,451	430	1,756	1890	32,052	2,361	4,298		1900	63,592		30,493		1910	64,356	1,083	36,400		1920	55,036	1,080	27,883		1929	59,278	1,116	28,640		1939	72,524	1,298	39,170		1950	128,643	5,600	92,808		1960	226,167	6,011	174,546		1970	302,173	8,057		
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1833	10,600**	6,951	627	991																																																																											
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1835	10,867	6,980	699	1,079																																																																											
1836	10,989	6,991	711	1,111																																																																											
1837	11,022	6,990	738	1,118																																																																											
1838	10,313	6,259	706	1,295																																																																											
1839	8,070	4,303	823	1,318																																																																											
1840	7,574	4,007	699	1,191																																																																											
1841	7,580	4,163	717	1,351																																																																											
1842	7,470	4,112	699	1,405																																																																											
1843	7,726**	4,264	647	1,405																																																																											
1844	7,899**	4,338	653	1,593																																																																											
1845	7,924**	4,214	633	1,483¶																																																																											
1846	7,783	4,207	560	1,491																																																																											
1847	8,702**	4,264	513	1,599																																																																											
1848	8,702¶,**	4,320	469	1,588																																																																											

*Sources: 1741–1880: Fedorova (1973, pp. 161, 203-204, 275-279). Obvious errors in arithmetic have been corrected. Others appear to exist and are marked ¶. Totals sometimes disagree with Tikhmenev (1863), as quoted by Petroff (1884); these are marked **.

1880: Petroff (1884, p. 33).

1880–1970: Decennial reports of the U. S. Bureau of the Census.

†Russian counts of Aleuts included Koniags as well. U. S. counts of Aleuts were not always made, and, when they were made, varying criteria of who was an Aleut were used.

‡The column labeled Russians included others before 1870 and includes all whites after 1870.

§In Russian usage a Creole was a person of mixed Russian and native blood.

¶At these points Fedorova or her source made an arithmetic error that cannot be corrected with the information available to me.

**At these points Fedorova's totals disagree with Tikhmenev's totals.

Table 2—Population of Native Villages in the Western Aleutians

Year*	Attu	Atka
1754–1757	60†	
1757–1758	50†	
1774	27†	
1825		60
1835	97	130
1860		220
1867	210	
1872	155	227
1880	107	236
1890	101	132
1920		56
1929	29	103
1939	44	89
1942	39–45	
1945	18‡	70
1950	0	85
1960	0	119
1970	0	88

*Sources: Fedorova (1973); Petroff (1884); decennial reports of the U. S. Bureau of the Census.

†Only heads of families counted.

‡Returned to Atka, not Attu.

“Kirilovskaia Bay* [is] the only place on the island where you can stay at anchor. This anchorage is somewhat sheltered from seaward by a reef off its middle, which requires caution in entering; there are some reefs on either side of it. It is dangerous to remain here in autumn or winter, when northerly gales are prevalent However when it was visited by Mr. Dall in 1873, he found nowhere more than 3 fathoms of water, and only the smallest class of vessels could enter it. The schooner Yukon anchored in Constantine Harbor” (Findlay, 1886, p. 682).

After 1849 we can for a while only follow the history of Amchitka by following the history of all the Aleutians. Governor followed governor of the Russian–American Company. Between depleted stocks of sea otters and greater conscientiousness for the welfare of the company employees, profits went down. Conservation measures, progressive for the times, were put into effect, starting with Rezanov’s orders in 1805 restricting the killing of fur seals (Bancroft, 1886, p. 446). In the 1820s and 1830s a series of measures were added to protect the most valuable sea mammals, such as interdiction of hunting in fixed areas for one or

two years and prohibition of firearms during the protected season (Fedorova, 1973, p. 189). In 1840 Governor Etholen extended the fallow periods to ten years (Bancroft, 1886, p. 582). By the end of the Russian period, the Atka Aleuts were allowed to take only 300 sea otters per year (Bergsland, 1959, p. 75).

The problems of the Russian government in holding a distant profitless territory in the face of vigorous expansion across the continent by the British and Americans and its general international posture, including its need to consolidate its influence in Asia along the Chinese border, led to the decision to give up Russian America. These problems are illustrated by the facts that the Russian–American Company actually played down the discovery of gold in 1848 lest it lose its monopoly, and then, when gold was discovered in Canada along the Stikine River in 1862, the Company asked for an armed cruiser to protect their possessions from being overrun by American and Canadian prospectors, but they never got that help (Gsovski, 1950, p. 29; Okun, 1951, pp. 245–249).

U. S. TERRITORY

In short, in 1867 the Imperial Russian government agreed to sell the territory to the United States. The purchase was not without argument. It was a year before the House of Representatives would appropriate the money needed to complete the transaction, but it was carried through, and Russian America became Alaska (Shiels, 1967).

After the purchase Alaska was nearly forgotten, and effective administration was only slowly extended to it. The only further actions by Congress were to establish Alaska as a customs district and to direct the Secretary of the Treasury to advertise for bids for the lease of the fur seal fisheries. With only 430 whites in the territory, there was little pressure to provide for local government. An army garrison was left in Sitka; but, when it was withdrawn in 1877 to help put down an uprising of the Nez Perce Indians in Idaho, there was no shadow of governmental authority left in Alaska. Indeed, in 1879 the inhabitants of Sitka had to call on a British naval vessel to restore order (Gruening, 1968, pp. 135–136). By 1884, however, after the throes of the Reconstruction following the Civil War were past, Congress constituted Alaska a “civil and judicial district,” and the laws of the state of Oregon were made applicable to it.

A very important aspect of U. S. ownership of Alaska was that it encouraged adventuresome men

*What we now call Cyril Cove, not Kirilov Bay, according to Jones (L. M. Gard, private communication, 1974).

to go there to see what they could find. They found more than furs and fish. There were numerous small and large finds of gold from the seventies on, and the return of the *Portland* in 1897 with a ton of gold from the Klondike made Alaska news throughout North America.

With some restrictions the fur seal fishery on the Pribilofs was leased in 1870 to the Alaska Commercial Company, and, when their lease expired 20 years later, the lease went to the North American Commercial Company. The taking of sea otters was nominally restricted to natives, but this rule was circumvented by enterprising white hunters marrying the comelier native women (Petroff, 1884, p. 18). Various traders competed for these skins, the Alaska Commercial Company being the most successful one. Bancroft (1886, p. 746) notes that "in 1885 they gathered nine-tenths of the world's supply of sea otter skins." Four years later, however, the Alaska Commercial Company was roundly denounced for closing its Attu store, leaving the Aleuts there without provisions or access to outside goods (Hinckley, 1972, p. 197). Presumably the long supply route combined with the scarcity of sea otters made it uneconomical to keep that trading post open; Petroff (1884, p. 22) indicates that even by 1880 the Attu people were beginning to turn to blue fox because of this scarcity.

Indeed, so far as the public record shows, the western Aleutians might not have existed at all. The only people remaining west of Umnak were at Attu and Atka. Unalaska, far to the east, with its good harbor continued to be visited by whalers until the collapse of that industry in the 1880s and by ships en route to northwestern Alaska. The very first U. S. court sessions to be held in the Aleutians were at Unalaska in 1901 (Wickersham, 1938, p. 322).

By the end of the century it appeared that the sea otters were nearly extinct and the fur seals in imminent danger of extinction. The conservation measures of the Russians had never entirely disappeared; for instance, the Pribilof Aleuts now refused to kill females (Jordan and Clark, 1898, p. 27). In addition to killing seals on land, another form of killing known as pelagic sealing had arisen. This had always been carried on by the Indians of Oregon and Washington, who were accustomed to going out in their canoes to take the animals in the course of their normal winter migration. The number of animals so taken was merely nominal then, but, after 1879, when schooners were introduced to transfer the canoes to their field of operations and care for them there, the industry began to make significant inroads on the herd. The rise of pelagic sealing thereafter was rapid. This

form of sealing was both inefficient in that not all the seals that were shot could be recovered and indiscriminate in that females could not be distinguished and were taken as well as males (Jordan and Clark, 1898, pp. 142-164).

Pelagic sealing was international and could not be controlled by our country alone. Since such sealing was largely a Canadian industry, in 1893 the United States entered into arbitration with Great Britain on the matter. Subsequent negotiations were extended to Japan and Russia as well, resulting finally in the Convention for the Preservation and Protection of Fur Seals of July 7, 1911 (Martin, 1946, pp. 200-232; Abegglen, Chap. 20, this volume). Thenceforth pelagic sealing was entirely forbidden. Fur seals were to be killed only on the islands where they came ashore to breed and have their young, the Pribilof Islands of Alaska, the Komandorskie Islands of Russia, and Robben* Island then of Japan. Canada and Japan, in return for forbidding pelagic sealing by their nationals, were to receive 15% of the harvest. Seemingly as an afterthought, that treaty also has a section out of 17 that says:

Each of the High Contracting Parties agrees that it will not permit its citizens or subjects or their vessels to kill, capture or pursue beyond the distance of three miles of its territories sea otters in any part of the waters mentioned in Article I of this Convention.

Thus sea otters too received international protection. It almost seems that the negotiators thought that the sea otter population was either already gone or too small to be viable, and this section was added just in case there was some chance they might recover. The Fur Seal Treaty remained in force until 1941, when it was abrogated by Japan; but, as detailed elsewhere (Abegglen, Chap. 20, this volume), it has been outstandingly successful in preserving and bringing back populations both of fur seals and of sea otters.

REFUGE STATUS

Following up on that treaty, on Mar. 3, 1913, President Taft, by Executive Order 1733, set aside all the Aleutian Islands† "as a preserve and

*Robben Island is now Russian and is known as Ostrov Tyulenii (Seal Island). It is little more than a reef, 600 m long and 10 to 35 m wide, lying off Sakhalin in the Sea of Okhotsk at latitude 48°30'N, longitude 148°38'E.

†Subsequent Executive orders have removed some of the islands and specific tracts from the Refuge. For the current status, see Bureau of Sport Fisheries and Wildlife (1974).

breeding ground for native birds, for the propagation of reindeer and fur bearing animals, and for the encouragement and development of fisheries.” The Executive Order itself is given in full in Appendix A of this chapter. Control over the Aleutian Islands Reservation was placed with the Department of Agriculture and the Department of Commerce and Labor. This put the Bureau of the Biological Survey in charge of all terrestrial species of animals and birds and the Bureau of Fisheries in charge of all aquatic species, including fish and sea mammals.

The Biological Survey had been established by the Secretary of Agriculture on July 1, 1885, as part of the Division of Entomology. It became a separate bureau under the Agriculture Appropriation Act of 1905. The Bureau of Fisheries had been established as the U. S. Fish Commission by Joint Resolution of Congress on Feb. 9, 1871. It became a bureau of the new Department of Commerce and Labor on July 1, 1903, and remained with Commerce when Labor split off on Mar. 4, 1913. These two bureaus were transferred to the Department of the Interior on July 1, 1939, were consolidated as the Fish and Wildlife Service on June 30, 1940, and were renamed the U. S. Fish and Wildlife Service in 1956. The two component parts were renamed the Bureau of Sport Fisheries and Wildlife and the Bureau of Commercial Fisheries. On Oct. 3, 1970, the latter became the National Marine Fisheries Service of the National Oceanic and Atmospheric Administration of the Department of Commerce. The Bureau of Sport Fisheries and Wildlife, renamed again the U. S. Fish and Wildlife Service on July 1, 1974, remains in the Department of the Interior (U. S. Government Manual, 1974–1975).

The Aleutian Islands Reservation was transferred to the Department of the Interior in 1939 together with the two bureaus that had control over it and renamed the Aleutian Islands National Wildlife Refuge on July 25, 1940. This was a change in name only and did not affect the continuity of management of the Refuge.

FOX FARMING

Aboriginally the blue fox occurred as a dominant form of the Arctic fox, *Alopex lagopus*, in the Near and Komandorskie Islands; farther north along the Bering Sea and Arctic Ocean coasts of mainland Alaska, few foxes show this maltese coloration. The early Russian explorers found these animals abundant in the Komandorskie and some of the Near Islands. The blue foxes later ranged in Prince William Sound and southeastern

Alaska were transferred there from this area. Similarly the early explorers found a dark-color phase of the red fox, *Vulpes fulva*, on the Alaskan peninsula and the eastern Aleutians. However, many of the central and western Aleutians had never seen a fox until the fox-farming splurge of the 1920s (Murie, 1959, pp. 287-295).

The very next year after the establishment of the Aleutian Islands Reservation, permits began to be issued for the use of individual islands for fox farming. The early permits (1914 to 1920) were unconditional and granted the permittee exclusive use of an island. Later permits carried requirements of stocking and annual reports of operations, but this proved in practice to be impractical, and there was a great deal of irregularity in submitting these reports (Murie et al., 1937, p. 74).

On May 23, 1916, a permit for Amchitka was issued to Peter Horozoff of Atka. There is no indication of the permit being used, and the permit was subsequently canceled. On Oct. 9, 1920, a permit was issued to “Native Residents of Atka” naming G. Stepatin, I. Petikoff, P. Horozoff, L. Sposnikoff, and P. Somekensky. This permit continued in force until June 22, 1929, when it was canceled, and Permit No. 189 was issued to the Atka Village Community [National Archives, File RG22, Box 652; Gray (?), 1937]. Renewal of this permit was finally denied in 1947.

In 1921 seven blue foxes were released on Amchitka. The method of conducting a fox farm in those days was to place a minimum breeding stock on an island and let natural increase take place. Very little care was needed. An island provided its own fence and protection, except for poachers, and the foxes depended on natural food for subsistence. No consideration was given to the conservation of any other resource. In fact, the presence of birds as a source of food was one of the main considerations in the fox-farm industry; it was well known that the best bird islands were the most productive fox islands.

By 1925 the number of foxes on Amchitka had increased to the point where they could be harvested, and 144 were trapped. In subsequent years over 4000 were taken off the island (Table 3). The last harvest was in the winter of 1946 and 1947; for this harvest we have an anecdotal description:

In 1946 we trapped blue foxes on Amchitka. We took the North Star to Adak [from Atka] and reached Amchitka on an FS [an Army freight ship]. Of the ten men, two trapped on the east side, two on the south side, four on the west side, and Philip and I on the north side. I went with Philip because I knew him better than anyone else there. I got 50 foxes and Philip 39. I spent two months with him, December and January. At the end of January he and I returned. All

Table 3—History of Fox Farming on Amchitka

Year*	Number introduced	Number trapped	Value
1921	7		
1922–1924		No report	
1925		144	\$ 7,200
1926		172	7,200
1927		No report	
1928		516	35,000
1929		564	35,000
1930		Not trapped	
1931		965	37,000
1932		660	18,150
1933		Not trapped	
1934		555	23,310
1935		Not trapped	
1936		500	20,000
1937		Unknown	
1938		Unknown	
1939		Unknown	
1940		Unknown	
1941		Unknown	
1942		Unknown	
1943		Not trapped	
1944		Not trapped	
1945		Not trapped	
1946		Unknown	
1947		441	?

*Sources: 1921–1936: Murie (1937).

1943–1945: Inferred from the evacuation of the Aleuts.

1947: Bergsland (1959, pp. 127-128).

the trappers returned. In April we all returned to the village from there. We passed four days on Adak and then went to Atka. We had killed 441 foxes altogether. (Paraphrased from a word-for-word translation by Bergsland, 1959, pp. 127-128.)

Trapping was a time-consuming business, and transportation between islands was thoroughly unreliable. Some sort of shelter had to be built on any island used for fox farming. In 1924, 11 barabaras (half-buried sod huts) were built as hunting camps on Amchitka and in 1925 3 more. The Site 20 mentioned by McCartney in Chap. 5, this volume, is the remains of one of these. In addition, a small village, consisting of five cabins, a boathouse, and a church, was built at the head of Constantine Harbor. The village was destroyed in the Aleutian campaign of World War II. All that now remains is a number of pits and a graveyard (Fig. 1), in which the only still legible headstone is for Anna Zaachney, 1884–1930. This is the Site 21 referred to by McCartney.

The story of fox farming deserves a monograph of its own. It is another case of a dream that started magnificently and then petered out with changes of fashion and oversupply of product.

From annual reports of the Alaska Game Commission* come the data given in Table 4 on the growth and decay of the Alaskan blue fox fur industry. In 1923, the first date they report, furs sold for over \$100 apiece. The price reached nearly this level again in 1929, but during the depression years the price dropped to \$30 and after the war fell further to nearly \$10 a skin. Production stayed high during the 1930s, but it was a moribund industry, and the war killed it off.

During the 1930s the Biological Survey developed the pattern of an annual summer trip into the Aleutians on the motor ship *Brown Bear*. On most of the islands the state of the bird population was the principal business, but on Amchitka the emphasis was on sea otters because that was where one of the principal remaining groups of them was to be found. Their existence was kept an unofficial secret; the service did not wish to advertise their presence since poaching was already going on.

It also became evident during this period that something was happening to the bird life of the islands. O. J. Murie led two expeditions to the Aleutians in 1936 and 1937, his purpose being "to investigate the faunal relationships on these islands with a view to obtaining necessary data on which to base satisfactory administration." In his trip report Murie says (Murie et al., 1937, p. 70): "There seems to have grown a general vague feeling that a fox island is 'good for only so long.' Probably in many cases this coincides with the length of time the bird supply lasts." At the end of his report he made recommendations as to which islands should be left fox islands and which should be returned to the status of bird islands. As to

Fig. 1—Aleut graveyard remaining from 1930s village (fence erected in 1968).

*Established Apr. 14, 1925.

Table 4—History of Blue Fox Farming in Alaska

Year*	Number trapped	Average price†	Total income (in thousands of dollars)
1923	1,718	\$101.50	174
1924	2,427	74.56	181
1925	5,493	49.83	274
1926	8,776	45.70	401
1927	11,021	61.48	678
1928	7,854	68.72	540
1929	8,520	99.10	844
1930	7,855	62.04	498
1931	6,922	28.14	195
1932	9,942	20.58	205
1933	9,960	30.35	302
1934	12,137	33.82	410
1935	10,281	24.36	250
1936	10,045	30.33	305
1937	11,433	29.50	337
1938	11,403	26.50	302
1939	10,444	22.38	234
1940	8,844	19.25	223
1941	6,804	26.64	181
1942	5,079	15.54	79
1943	1,783	34.00	61
1944	1,495	22.59	34
1945	1,806	24.81	44
1946			
1947	929	11.00	10
1948	430		
1949	210		
1950	200		
1951	100		
1952	70		
1953	10		

*Source: Annual reports of the Alaska Game Commission.

†I cannot account for the fact that these average prices sometimes differ markedly from those to be inferred from Table 3.

Amchitka the report said (Murie et al., 1937, p. 196):

... the ideal use of this island would be for wildlife, such as waterfowl and sea otters. However this island plays an important part in the life of the Atka natives and under present conditions we could hardly withdraw the island from fox raising.

However, the following solution is suggested. First, it is barely possible that the importance of fox raising may be lessened in the future due to events at present unforeseen. In that case Amchitka could be put to its most fitting use as outlined above. Or, the natives may be induced and assisted to practice more controlled and intensive fox farming on Atka Island itself so that Amchitka Island will not be needed. It should be recalled that at present the Atka natives have Atka, Amlia, and Amchitka, all large islands. We feel that it is well, in some manner, to be alert for an opportunity to release Amchitka without working undue hardship on the native Atka community.

That opportunity came with the collapse of the fox-farming industry.

Later Murie (1959) returned to the theme of the drastic reduction of the bird population, especially on Agattu. He quoted Clark (1910) as saying that the Hutchins Goose (now called the Aleutian Canada Goose, *Branta canadensis leucopareia*) was in 1906 "the most abundant bird on Agattu, where it breeds by the thousands." In 1937 his party managed to find less than half a dozen nesting pairs there.

Foxes did not affect all species of birds as drastically. Murie (1959, p. 297) says:

The importance of birds in the blue fox diet is evident ... they furnish 57.8 percent of the food, though the percentage varies on different islands, depending on availability. Land birds are relatively unimportant. They are hard to capture and do not gather in large groups. But the concentrated colonies of petrel, auklets, and related species furnish rich hunting grounds.

Today the Aleutian Canada Goose is on the Secretary of the Interior's list of threatened species (Bureau of Sport Fisheries and Wildlife, 1973, p. 288) and apart from game farms apparently survives only on Buldir Island. We may wonder, how did the Biological Survey come to commit the ecological blunder of introducing foxes onto these islands? Three reasons present themselves. Executive Order 1733, which set up the Aleutian Islands Reservation, specified "... the propagation of reindeer and fur bearing animals" as one function of the Reservation. H. Douglas Gray (private communication), retired Alaskan Wildlife Agent, told me that in 1921 the Biological Survey was staffed in this part of the world with old trappers and other fur-oriented people. They were interested in what the land could produce and naturally turned to this "highest and best use." Probably too they wanted to help the economically depressed Aleut people, with whom they could not help but sympathize.

Before World War II the Aleutian Islands Reservation was administered from Kodiak. In October 1948 the refuge received its own manager, Robert D. Jones, Jr., to be stationed at Cold Bay and furnished with a dory to get about in. Jones had come to the Aleutians during the war, spending a little over a year on Amchitka itself.

The goal of eliminating foxes from Amchitka first appears on the record in March 1939 in Gray's "Proposed Plans for the Administration of the Aleutian Islands Wildlife Refuge," which said, "Amchitka Island has been taken out of fox farming production." Then the war put these plans aside. In 1948 Jones took them up again. How to do it? Control was not enough; complete elimi-

nation would be the only satisfactory answer. In 1950 Jones experimented with strychnine-loaded pellets of seal blubber left along established fox trails. That summer it did not work, but, in the harsher conditions of the following winter, the pellets were eaten and were effective. Rat poison (1080) was also set out, and, although the rat population of the island has never been more than reduced, their 1080-laden carcasses killed off the feral dogs and cats left by departing soldiers. The poison-pellet campaign continued and was enlarged, supplemented by the shooting of such foxes as were seen. By 1960 tracks of a single fox were found around an old mess hall not far from Constantine Harbor. Signs of four to six others were found elsewhere on the island but nowhere any signs of litters or dens. These, it turned out, were the last foxes on Amchitka. After 40 years they were gone (Jones, 1960; Berns, 1960).

WORLD WAR II

On June 3 and 4, 1942, planes from a Japanese carrier force struck Dutch Harbor on Unalaska. On June 7 Japanese troops landed on Kiska and Attu. It was part of a plan to draw support away from the impending Battle of Midway. In that respect it failed; Admiral Yamamoto lost all four of the carriers he had committed to the Midway engagement, and the tide of battle was turned in the Pacific. On the northern front, however, Japan was ahead. War had come to Alaska, and henceforth service in Alaska warranted the Asiatic-Pacific Campaign Medal and ribbon.

On Kiska there had been a 10-man Navy weather observation team. All were captured, although one man held out for 50 days, eating grass, worms, and shellfish. These men lived out the war as prisoners of war in Japan; they were put to work in forced-labor prisoner gangs in shipyards and steelworks. All survived to return home after the war (Garfield, 1969, pp. 80-81, 310).

Attu village had been there since aboriginal times and was thus one of the oldest villages in the chain as well as the most distant from the mainland. Accounts differ as to how many Aleuts were on Attu, various accounts putting it at anything from 39 to 45.* Fifteen of them were children. There was also the schoolteacher and his

wife, Charles Foster Jones and Etta Jones. [Golodoff (1966), an Attu Aleut, remembered them as Gene and Jane Foster.] Jones died in the aftermath of the occupation; it is not clear whether he was shot trying to escape or committed suicide rather than surrender (Garfield, 1969, pp. 81, 310; *New York Times*, 6/21/43, p. 3; Bergsland, 1959, p. 126). Mrs. Jones was separated from the others, sent to a prisoner-of-war camp at Zentsuji, Japan, and returned to the United States in October 1945 (*New York Times*, 6/21/43, p. 3; 10/19/45, p. 3). In September 1942 the Japanese evacuated the Attu Aleuts to Otaru, Hokkaido. (The *New York Times* erroneously reported them as having been taken to Sakhalin, but in 1943 their sources of information from Japan were poor.) The Attu people were put to work digging pottery clay.

After the war the survivors were flown to Okinawa and then to Manila, from which they went by ship to San Francisco, by train to Seattle, and by ship to Adak. Golodoff says that they wanted to return to Attu, but that "we were not enough people so the Government wouldn't let us go to Attu. The Government told us to live with the Atka people." The reason that the Bureau of Indian Affairs gave was that Attu was too distant to supply, and the villagers were sure to need a subsidy and other assistance. The Attuans went to Atka, arriving there on Dec. 11, 1945, 18 of them: 4 men, 3 women, and 10 children, the oldest 15, in five families plus a baby boy born to Mrs. Alfred Prokopioff about the time they left Japan (*New York Times*, 10/19/45). The rest of them had starved on the scanty and unfamiliar diet the Japanese had given them.

In the meantime, in June 1942 the Americans evacuated all remaining Aleuts west of Unimak, including those on the Pribilofs. Atka itself was evacuated on June 13-14, just ahead of a Japanese air attack from Kiska. The Aleuts were taken to various places in southeastern Alaska: the Pribilof Islanders to Funter Bay on the north end of Admiralty Island near Juneau, the Atka people to Killisnoo near Angoon on Admiralty Island, the Nikolski people to Wards Cove near Ketchikan, and others to Bernet Bay near Sitka. Here they remained for three years, until June 1945, suffering somewhat from the different environment and resulting respiratory diseases and from the cultural shock. Duncan (1945) ends his article on their prospective return, "But how are you going to keep 'em out on the Chain after they've seen Juneau? Indian Service men have discovered a little wavering, especially among the younger Aleuts. 'We'll go back to the island now,' some of them are saying, 'and see how we like it. If we don't like it there, maybe somehow we can get back here

**New York Times* (6/21/43): 42 Aleuts and 2 whites. Duncan (1945): 45 Aleuts and 2 whites.

New York Times (10/19/45): 40 Aleuts and 2 whites. Berreman (1955, p. 57): 42 (not clear if whites included).

Golodoff (1966): 40 Aleuts and 2 white.

Garfield (1969, p. 79): 39 Aleuts and 2 whites.

again.'” More seriously, Berreman (1955, pp. 52-53) says of Nikolski that the wartime removal, the postwar return to find their village a shambles, slow and inadequate resolution of their losses, and general frustration at not being able to satisfy the wants acquired during the removal were important new factors in the continuing disintegration of the old Aleut ways and social integration.

These evacuations left the Aleutians an empty and open field for the prosecution of the military campaign. It was to prove a messy, wet, inefficient operation. The Americans concentrated on harassing the Japanese-held positions with as many bombing raids as weather and supplies would permit and developed a series of ever more forward bases to facilitate that effort and to serve as bases for finally dislodging them. The Japanese concentrated on holding, supplying, and reinforcing the positions they held; they started a few desultory movements forward, but these were never carried through. For both sides the Aleutian front was a war poorly supplied and equipped.

Conditions made the war dangerous in more ways than just being shot at. Today Reeve Aleutian Airways flies the chain on a regular basis; you can count on delivery safely to your destination with seldom more than a few hours' or a day's delay due to fog or winds. During World War II there were few of the aids used today: only beacons and radio direction finders, and those were scarce. There was “a complete lack of radio ranges, lighting facilities, and other navigational aids west of Umnak” (Craven and Cate, 1950, p. 397). Aircraft flew visually where often there was little visibility, and ships went where there were no charts more recent than those from Russian times. Many an airplane crew was lost for no reason other than that they could not find their way back or down.

In June 1942, just after the Americans discovered the presence of the Japanese on Kiska, the submarine S-27 was sent out to find out if the Japanese had yet occupied Amchitka. The S-27 went onto a reef, and the crew had to abandon ship, setting up camp in the church in the unoccupied village at the head of the Constantine Harbor. Six days later a patrolling PBY plane found them there, and the next day, June 26, they were evacuated back to Dutch Harbor. There had been no Japanese on Amchitka.

Bombing missions could be run from Dutch Harbor or Umnak, but it was a long run and costly in men and machines. A more forward base was needed. The Army Air Corps nominated Tanaga; the Navy nominated Adak. The Joint Chiefs of Staff had to adjudicate and chose Adak because the fine harbor there made it a natural for staging later amphibious operations (Conn, Engelman, and Fair-

child, 1964, p. 270; Morison, 1968, pp. 12-13; Craven and Cate, 1950, p. 374). Scouts were put ashore on August 28 to check for the presence of the enemy; there was no sign of the enemy, and the main force of 4556 men went ashore on the 30th. Within 10 days an airstrip had been built by putting a dike around a shallow lagoon and closing off the tide from it. The strip was hard-packed sand and was later covered with steel matting. Today's airfield on Adak is concrete, at the same place, and it still has to be kept dry by pumping the ditches alongside.

On the 10th of the next month, a small party reoccupied Atka. Atka had been used at various times before for seaplane operations, and a land strip was now built there.

In between these islands and Kiska lay two other large islands, Tanaga and Amchitka, with land flat and low enough to be considered seriously as possible sites for airstrips. The official army history indicates that the initial plan was to move onto Tanaga (Conn et al., 1964, pp. 270-276). Reconnaissance parties had been sent to both islands at the end of September, the one to Amchitka being made by 34 scouts on September 23. The History of the Alaskan Air Command says of this reconnaissance: “In the report made by Col. Verbeck, it would seem impossible to construct a suitable runway of any type on the island. With the exception of the recommendation that a landing field could not be built on Amchitka, Colonel Verbeck's report was of great value in the preparation and planning of construction” (History of the Alaskan Air Command, 1952). A plan was drawn up to move onto Tanaga on November 1, but reviews carried all the way up to General Marshall eventually brought back the decision to use Amchitka, the more forward island (Conn et al., 1964, p. 275).

Preceded by an aerial strike to find out if any Japanese troops were on the island and to destroy the village on Constantine Harbor, including the church, so that there would be no hiding place, a new survey was made on December 17–19. It was led by Colonel Talley, who had made his reputation in the speedy job of airstrip building on Adak. His reports were instrumental in confirming the change of the proposed base from Tanaga to Amchitka. He predicted two to three weeks would be needed for a fighter strip and three to four months for a main airfield (Conn et al., 1964, p. 275; Craven and Cate, 1950, p. 374). His party found signs that Japanese had been there—a boat with no water in it from snow that had fallen two nights before and unweathered rifle cleaning patches along a trail. A story told during the AEC occupation of Amchitka was that the airstrip was

built according to Japanese survey stakes, but Talley (private communication, 1976) himself says that what they found was several test pits showing soil cross sections.

The Japanese had, in fact, made two abortive sorties toward occupying Amchitka. One in October 1942 turned back when their intelligence service warned Admiral Hosagaya, falsely as we know and he did not, that a strong U. S. Navy task force was in the vicinity. The other in late November was deterred by heavy air raids (Garfield, 1969, pp. 148-149).

On Jan. 12, 1943, 1945 men, under the command of Brigadier General Lloyd E. Jones,* went ashore at the head of Constantine Harbor (Figs. 2 and 3). It was in the tail end of a storm, and the worst of the winter was still ahead, probably as miserable weather for a landing as U. S. troops have ever had to make. Their first priority task was to make a landing strip, and this they did in 5 weeks' time; so on February 16 a P-40 squadron was able to come in and land. Aleutian weather is such that often even in the worst of clouds and fog there is a hundred feet or so of somewhat clearer air down near the water. A graben crosses Amchitka, dipping gently under the water at both ends to form Constantine Harbor and Makarius Bay. The new Amchitka fighter strip (Fox Runway) took advantage of these climatic and geomorphological peculiarities by going right from the water's edge gently uphill to the southwest (Fig. 4). This water-level strip saved many a pilot's life. The Navy also had a PBY patrol squadron on the island that used a ramp into the sea at the foot of Fox Runway.

After Fox Runway was complete, work was started on a bomber runway (Baker Runway). In mid-June 1943 a third cross runway (Charlie Runway) was started. In early 1944, after the Aleutian campaign itself was over, construction began to enlarge Baker Runway to support B-29's in bombing attacks on the Japanese homeland. The runway construction was completed, but the B-29's never arrived: Rapid advances in the Central and South Pacific and poor weather in the Aleutians made an Amchitka base less desirable than bases in the Mariana Islands and in China (Craven and Cate, 1950, pp. 396, 400-401; History of the Alaskan Air Command, 1952). [B-29's finally made it to Amchitka 4 years later when two of them landed there after making observations of the eclipse of May 8-9, 1948. This was the first time that aircraft were ever used for this purpose (Kinney, 1949).]

*For whom Jones Lake is named (see Geological Survey map in the pocket at the back of this volume).

Fig. 2—Troops landing at the head of Constantine Harbor, Jan. 13, 1943. (U. S. Army photograph SC 171235-B.)

Fig. 3—Scene of 1943 landing in May 1974.

Fox Runway is no longer useful. It was concreted in the 1944 construction program, but, sometime before the eventual pullout in 1950, trenches were cut across it since it was no longer usable. Winter storms and the 1957 tsunami have built a beach ridge across its foot; and the Rat Island earthquake of Feb. 3, 1965, caused some of the fill land in the foreground of Fig. 4 to settle and block its drainage to the harbor (Fig. 5). Baker Runway was renovated and improved during AEC occupancy of the island and is a good runway. A beacon and landing lights remain, but these are only operational when there is a party of people on the island. Charlie Runway has not been maintained. It was used once during the AEC occupancy when crosswinds did not permit use of Baker Runway, but the landing was so rough that it was never repeated.

Fig. 4—Foot of Fox Runway, Mar. 4, 1943. Motor pool is in foreground, P-40's on taxiway in rear, and derelict B-24 in water beyond strip. (U. S. Army photograph SC 571335.)

The American presence on Amchitka was discovered by the Japanese on Jan. 23, 1943. Bombers immediately started hitting the runway under construction, but these attacks were kept up only a month. The very geography is against an attacker acting from Kiska. Bird Cape, at the northwest end of Amchitka, is only 50 miles from Kiska; a small camp and radar site was set up there which, weather permitting, was able to warn those at the airstrip 30 miles to the east of approaching airplanes.

Occupation of Amchitka, although producing no immediate spectacular results, did help make the Japanese hold on the Aleutians hopeless. Systematic supply of their garrisons became hazardous, requiring a powerful task force to drive a convoy of ships through the air and naval blockade. Just such an attempt was foiled by the Navy on March 26, and the Japanese doom was sealed.

Kiska was the chief target of planes from Amchitka; any intermittent letup in the cloud cover permitted a bombing run on a target only 80 miles away. Weather also played its part in making Kiska the main target in another way. Bombers sent to Attu frequently found that island closed in and unloaded on Kiska on the return trip; so in April only 30 sorties were actually made against Attu. These did other important work, however; the aerial pictures they took constituted almost the sole source of intelligence about Japanese troop strength (Craven and Cate, 1950, pp. 376, 379).

The overriding purpose of the American military forces was to dislodge the Japanese from the islands they held. On May 11, 1943, a force of 14,826 men under Major General Albert E. Brown landed on an Attu defended by about 2500 men under Colonel Yasuyo Yamasaki. It was expected to be a short action, but, in fact, it lasted until May

Fig. 5—Foot of Fox Runway, May 1974. Note subsidence of fill land from the 1965 Rat Islands earthquake.

29, when only 28 Japanese remained alive to become prisoners. The American forces suffered 3829 casualties, including 549 dead, 1148 wounded, 1200 with severe injuries from the cold, 614 with disease (including exposure), and 318 other casualties. Many mistakes were made, especially in not taking good advice about the conditions to be expected in the Aleutians. We are told that the services profited greatly from this experience (Garfield, 1969, pp. 208-258).

On May 11, of 168 Air Force planes in the forward area, 86, or 51%, were on Amchitka (Craven and Cate, 1950, p. 381).

Kiska remained in Japanese hands. A force of 18,006 men, including 4983 Canadians, landed there on Aug. 18, 1943. As it turned out, the Japanese had been able to evacuate their forces on July 28, and the U. S. and Canadian troops encountered only mines and booby traps left by the departing Japanese. There were 208 casualties: 28 dead, 50 wounded, and 130 with trench foot (Garfield, 1969, p. 288).

The expulsion of the enemy left the North Pacific forces without an immediate mission. One possible one was using the Aleutians to attack northern Japan or the Kuriles. The Kuriles had been Russian since the seventeenth century but had been taken by the Japanese as part of the spoils of the Russo-Japanese War of 1904 and 1905. They had come to be considered part of the Japanese homeland, and Shimushu and Paramushiru, the first and second of the Kuriles (from Kamchatka), had been developed into major bases of the Imperial Japanese Navy. (Since World War II the Kuriles have become Russian again.) During the time between the retaking of Attu and the landing on Kiska, the Army Air Corps used the Aleutians

to stage the first strikes against the Japanese homeland since the Doolittle raid of April 1942 (Thirty Seconds over Tokyo). A raid on July 18, 1943, found the Japanese on Shimushu and Paramushiru unprepared; a second on August 11 found them ready and waiting, and two out of nine planes failed to return home. On September 11, 10 out of 19 planes failed to return, although 7 of them got to Petropavlovsk to be interned. The next year the tempo increased, and, including photographic reconnaissances, there were over 100 sorties over the Kuriles from the Aleutians. Airstrips were prepared on Amchitka, Adak, and Shemya in 1944 for a possible full-scale operation against Paramushiru, but the tide of war elsewhere caused that to be unnecessary, and the airfield expense has to be written down as one of those things called for in the prodigality of global warfare. In the end the mission of the troops remaining in the Aleutians was to tie down an even greater number of troops and planes in the Kuriles.

Amchitka was the forward fighter-bomber base for the Aleutian campaign, but it was also the end of the line. The early garrison lived in tents, at first with mud floors (Figs. 4 and 6). Wet feet and cold C rations were the order of the day. There were no recreations except what the men could invent, and the normal outdoor athletics of healthy young men were hardly attractive in cold mud. There was just endless waiting.

Thus, when word got out that there was archaeological loot to be had, digging reached almost epidemic proportions. Lieutenant Paul Guggenheim, a doctor who had been a student helper with Hrdlička on Amchitka in 1937, wrote the commanding general asking permission to reconnoitre the island and excavate archaeological sites. This was granted, but there was no effective way to control casual collectors; General Jones thought it inadvisable to use rigid military control in the absence of orders from Washington. In a misguided effort to encourage a scientific approach, several official memoranda were issued from force headquarters, one of which is reproduced in Appendix B. These memoranda served to create interest rather than to control it, and all easily available sites were thoroughly pillaged. Many fine collections of artifacts were made, unfortunately without the proper concern for provenance; a few of these have ended up in the Smithsonian and other museums. One might say in hindsight that this digging should not have been permitted, but the realistic view is that, under the very trying circumstances of life on Amchitka, this recreation was a sanity saver (Guggenheim, 1945).

One looks now at Amchitka, especially in the southeastern section around the harbor and the

Fig. 6—Troop tent, winter 1944–1945. (Photograph courtesy of R. F. Shary, Anchorage.)

three runways, and the signs of man's past presence on the island seem almost overwhelming (Fig. 7). One wonders just how many men were there to warrant all that construction. As we have already seen, the initial landing on Jan. 12, 1943, consisted of nearly 2000 men. Air Force records show that their strength was 3040 on June 5, 1943, and 3027 on June 30, 1945 (History of the Alaskan Air Command, 1952). Navy records are less precise and merely indicate 1200 men in 1943 (Anonymous, 1947, p. 182). Army records I have not seen. Records of the Corps of Engineers indicate that by 1945 there were facilities for an authorized troop capacity of 16,134 men, and their total construction costs had come to over \$34 million. The same records indicate that there were then 1873 Pacific huts usable, each with a capacity of 8 men (Corps of Engineers, 1945). Thus it appears that during the actual campaign there were about 5000

Fig. 7—Roads and buildings left from World War II. (Photograph courtesy of E. D. Campbell, Energy Research and Development Administration.)

men and that this number may have nearly tripled later in the war.

The early primitive tent quarters and steel-mat runways were improved as time went by. In 1944, runways were paved and more permanent quarters were built. Most of these are of the semicylindrical shape commonly called Quonset huts. The true Quonset hut has metal ribs and skins; most of the huts on Amchitka were of the same shape but were made of a masonite-like material and are properly called Pacific huts; they were developed by a Colonel James Lang as a steel-saving proposition. KD (Knock-Down) huts of wood were also used. In general, these huts were dug into the peat, the peat removed forming berms around the sides and ends as additional protection against the wind and wet (Fig. 8). They were built by hand labor from material brought across frozen ground during the winter by crawler-type vehicles, accounting for the fact that there are no roads to many of them, only foot trails. In later years the garrison also built many boardwalks along commonly traveled routes which are now in the process of rotting away and being covered over by encroaching vegetation.

THE POSTWAR YEARS

Some troops stayed in the western Aleutians for a while after the war. Amchitka itself was evacuated by August 1950 (Jones, 1960, p. 9). Attu was empty by March 1949, although at some time since the Coast Guard has put 35 men there to run a loran station. Atka was placed in caretaker status in January 1944. Kiska was not held for long after it was found that the Japanese had abandoned it, perhaps because there is much unexploded ordnance on it. Shemya was evacuated in 1951 but was later used as a refueling stop by Northwest Airlines on the Anchorage–Tokyo route and now again has an Air Force station on it. Adak has been occupied continuously and indeed has gained importance when the Navy headquarters was removed from Kodiak in 1971 and the refuge headquarters to Adak from Cold Bay in 1972. Adak now has the distinction of being the station farthest west in the United States where military dependents are allowed.

In 1951 a proposed new project involved Amchitka, foreshadowing its recent use by the Department of Defense (DOD) and the U. S. Atomic Energy Commission (AEC) as a site for nuclear explosions. Project Windstorm was a response to a military need for information about the cratering potential of nuclear explosions. The DOD wished to fire two 20-kt explosions, one surface burst and one shallowly buried. For this

Fig. 8—Pacific hut protected by peat berms, winter 1944–1945. (Photograph courtesy of R. F. Shary, Anchorage.)

they required a site having “a minimum thickness of 150 feet of incoherent detrital material in which the seismic velocities would be essentially uniform” (Piper, 1952). For some reason it was thought this could be found on Amchitka. Two drilling parties were sent to the island, and in early 1951 they drilled 34 test holes at various positions to the northwest of where Cannikin was fired in 1971 (Chap. 1, Fig. 11). No such conditions were found, and the exploratory drilling was stopped on May 10, 1951. The scope of the project was reduced to the 1.2-kt level and became the Jangle Surface and Jangle Underground shots fired in November 1951 at the Nevada Test Site.

In the early 1950s much of what is now old, rotten, and weatherbeaten was still in very good shape. This, of course, was also true in other former fields of war, and there too a great deal of material remained, surplus to the military but potentially valuable to someone. Some time after the war, probably about 1951, salvage rights were put out to bid. The original bid invitations brought no response; so the Navy, which was acting as the executive agent for the military in this matter, entered into negotiation with Bankers Life and Casualty Company of Illinois. After prolonged negotiations, a figure of \$318,000 was agreed on

for all the salvage rights on 13 islands of the Aleutian chain (Anonymous, 1961). This firm intended to do the job with Japanese labor, but the unions objected; so they were forced to abandon this idea and sublet the rights (Robert Atwood, private communication, 1973). The first salvage operation was by Aleutco, a Seattle firm whose name suggests that it was formed ad hoc for this particular job. Aleutco took only items of large value that could be easily transported, things on wheels so to speak: trucks, generators, compressors, and installed real property, such as motors. A second salvage was conducted in 1953 by General Metals of Tacoma. They salvaged metals, particularly copper and lead (R. D. Jones, private communication, 1973). These were "high-grading" operations; for instance, the copper of telephone wires was often taken by felling the poles, but this was only done in the southeastern part of Amchitka where there was much of it. The salvage rights have since either been bought back by the government, as in 1955 when Shemya was to be made a refueling stop for Northwest Airlines, or simply expired, as seems to have happened to Amchitka.

During the years 1954 to 1957, a Distant Early Warning radar network (the so-called DEW line) was built across northern Alaska and Canada. A DEW line extension was run into the Aleutians starting in 1957. The communications portion of the DEW line was called the White Alice system. (Since then the White Alice system first became a separate entity serving also the isolated bush towns of Alaska, and now large portions of it are melded into the statewide telephone service run by RCA Communications.) In connection with White Alice operations and the DEW line extension, Western Electric crews were on Amchitka from 1959 to 1961. Their mission was to run a relay station using a 30-ft antenna dish to bridge the 400-mile gap between Adak and Shemya during the time those stations had only 60-ft dishes. These and other main DEW line stations now use 120-ft dishes and have ample power and sensitivity to bridge such gaps. The actual White Alice site is in an area not damaged in World War II; it is a little over a kilometer northwest of where Cannikin was later to be fired (Chap. 1, Fig. 11), coincidentally fairly close to the 1951 proposed site for Project Windstorm. From this short time activity comes the name of the White Alice Creek that drains the Cannikin site and figures elsewhere in this book.

POSTWAR REFUGE MANAGEMENT

Amchitka and the western Aleutians were still part of the Aleutian Islands National Wildlife

Refuge, these other activities being tolerated under the original provision of Executive Order 1733 that "the establishment of this reservation shall not interfere with the use of the islands for lighthouse, military, or naval purposes. . . ." The Department of the Interior resumed management over most of the refuge territory in 1948 with the appointment of Jones as Refuge Manager. Reading his reports from 1950 on, we see a series of activities that continued year after year. Some of them were pure housekeeping matters, such as permits issued, poachers caught, and trips made. There are also extensive lists of birds seen and identified with their times of arrival and nesting. There are details on rats trapped on Amchitka (Brechtbill, Chap. 12, this volume). There are lists of plants. But the dominant themes, especially for Amchitka, are the sea otter and the Aleutian Canada Goose.

In 1958 the refuge was described as follows:

The Aleutian Islands National Wildlife Refuge was established in 1913 to insure protection of the native birds and fur bearers, to provide for the propagation of reindeer, and to encourage and develop the fisheries. As we now know, the propagation of reindeer is often inimical to populations of nesting birds, and to the range itself if the animals are not carefully managed. That and the Aleut people's lack of interest in reindeer has dictated a "go slow" policy in reindeer propagation. Because of remoteness and the existence of severe weather conditions, development of the fishery has proceeded slowly. Even today the inshore fishery of all but the eastern end of the Refuge is rarely utilized. The Japanese high seas fishing fleet is currently engaged in the development of the off-shore fishery. It is mainly in the field of native bird protection and the management of fur bearers that Refuge administration has moved. The redevelopment of a sizeable population of sea otters has been the most significant step in the history of the Refuge. When in 1913 the Refuge came into being a sea otter was a rare specimen, but there are now more than 20,000 of the curious little animals within the Refuge boundaries.

(In spite of the comment about reindeer, caribou, a closely related species, were introduced to Adak in 1958 and 1959. They are kept under close control by hunting; indeed, G. Vernon Byrd, the present Assistant Refuge Manager, while in the Navy on Adak had as part of his duties as Base Conservation Officer assisting the Fish and Wildlife Service in the management of this game herd.) The sea otters of the western Aleutians, and especially Amchitka, were extensively studied, resulting in a Ph. D. thesis by Lensink (1962) and a monograph by Kenyon (1969). Kenyon describes at length the experiments that have led to recent apparently successful transplants of sea otters from Amchitka and elsewhere where the population is now stable into parts of their former range where they had been completely extirpated by hunting (Abegglen, Chap. 20, this volume).

I have already indicated the plight of the Aleutian Canada Goose and how the introduction of foxes to most of the Aleutians all but wiped them out. Jones' reports give a picture of a dedicated long-term effort to reverse this sad history. Foxes were extirpated from Amchitka by 1960 and from Agattu by 1968,* the latter island being the one that Murie (1959) had believed was once the very best island for the geese. Jones suspected from Murie's reports that these geese had survived in small numbers on Buldir and verified this in 1961. In 1963, 18 goslings were removed from Buldir and sent to a game farm in Colorado. Sixteen of these survived and formed the nucleus of a captive population now at the Patuxent game farm in Maryland. Thus Jones (not single handedly, of course, but as the driving force) had done away with the primary enemy of the geese on two islands, had found a surviving nucleus of them, and had arranged for them to be cared for and to multiply in numbers. It only remained to reintroduce the geese to these islands, when the DOD and later the AEC took over Amchitka for other purposes and frustrated the long-term plan.

Actually it has not been quite as bad as all that. In the spring of 1971, the Fish and Wildlife Service did bring back Aleutian Canada geese to Amchitka using AEC support to transport them. They did not bring them back in an effort to transplant, however, so much as in an experiment on transplanting methods. The proven system for transplanting migratory birds consists of bringing a group of adults into a place and holding them in cages. The adults rear young, and these young, who are imprinted with this place, are released. This standard method requires a crew to provide continuous care for several years, usually about 3. What was tried in 1971 was to see what could be done on a much shorter time scale. Seventy-five geese were brought in and released shortly before the nesting season. Very few live birds were seen after the release, and the few dead birds seen had either been killed by eagles or eaten by them after death from other causes. There was no evidence of production of young birds or the return of the geese in the following years. Thus this experiment proved unsuccessful. The Patuxent game farm has yet other Aleutian Canada geese, and in 1974 the Fish and Wildlife Service reintroduced them to Agattu and in 1976 started to return them to Amchitka.

There has been a slow change in management purposes for the refuge over the years. At the

beginning in 1913 it was reindeer, fur bearers, and fisheries. In 1958 it was not reindeer but sea otters, birds, and, to a much smaller extent, fisheries. The most recent statement of purposes is in a recent Wilderness Study Report (Sekora, 1973):

1. To maintain at minimum recovery levels all native species normally associated with the environments found on the Refuges—more specifically, to protect and preserve populations of colonial nesting birds, marine mammals, and other wildlife indigenous to the Aleutian Islands and their adjacent waters.

2. To assure the survival in a natural state of each of this Nation's plant and animal species—more specifically to restore the Aleutian Canada goose and sea otter populations to former ranges and levels of abundance.

3. To contain all lands or networks of lands of national significance whose benefits to the public can best be achieved by the distinctive competence of the National Wildlife Refuge System—more specifically to preserve watersheds which contribute materially to the production of salmon stocks.

4. To seek out, identify, designate, preserve, and appropriately use sites and objects on refuges that are recognized to have esthetic, historic, geologic, archeologic or scientific values.

5. To raise to optimum levels the kinds, range, amount, and quality of wildlife and wildlands—oriented recreation—more specifically, to manage game populations [caribou] on Adak Island as a harvestable resource.

6. To establish and preserve in a natural state selected areas for reference observation, scientific study, and/or specialized public use, and in which the major ecological communities in the system are represented.

Statehood came to Alaska in 1959 after a long and difficult struggle. The Territory of Alaska had never had much control over its natural resources, and indeed this had been one of the sore points that led to the demand for statehood. In the Aleutian Islands National Wildlife Refuge, statehood has meant some sharing of responsibility by the Department of the Interior with the newly established Alaska Department of Fish and Game. (The old Alaska Game Commission ceased to exist.) Today one must have a state fishing license to fish for salmon or Dolly Varden on Amchitka. More important was the control and management of the sea otter. Technically the State acquired jurisdiction over sea otters at sea, between the lower tide line and the 3-mile (5-km) limit of U. S. sovereignty, and the Department of the Interior kept jurisdiction over sea otters on land. This was a fine and artificial line that did not meet the practicalities of the situation. In practice, the State has managed the sea otter resource, issuing permits for their taking for such purposes as research, transplanting them into other parts of their former range, and harvesting their furs for sale where their density of numbers permitted. All this, of course,

*So reported Jones, but he was mistaken. A crew bringing geese to Agattu in the spring of 1974 found over a hundred foxes still there.

has been rendered moot by passage of the Marine Mammal Protection Act of 1972, which has returned responsibility for all sea mammals to the Department of the Interior and has resulted in a moratorium on taking them for any purpose (Abegglen, Chap. 20, this volume).

TSUNAMIS

Before finally turning to the events that led to nuclear testing on Amchitka, mention should be made of another external influence on the island, one provided by nature, not man. It is well known that the Aleutians are a region of the world that is very active seismically (Gard, Chap. 2, this volume). Earthquakes sometimes give rise to tsunamis or seismic sea waves (often misnamed "tidal waves"). Cox and Pararas-Carayannis (1969) list tsunamis that have been felt in Alaska so far as the historical record reveals them. Presumably tsunamis have been felt in the western Aleutians for as long as those islands have existed, but they do not appear in the record until 1944, after which there are 15 entries (Table 5). These were all recent enough that measurements at standard tidal stations exist on them; four of them had amplitudes of a meter or greater at Attu or Adak. For three of them observations at Amchitka itself are available.

The 1957 tsunami, which arose from a source near Unimak in the eastern Aleutians, is mentioned by Jones in his Narrative Report of 1957:

... A tidal wave reaching 13 ft above high tide followed the most severe of the earthquakes, washing debris onto the lower part of the islands and creating additional damage at Adak. At Adak agitation of the water sources for trout hatchery apparently released the accumulated products of decomposition and temporarily polluted water flowing in the troughs. Ten to eleven thousand fingerlings were lost before the situation was restored. While the Refuge Manager was on the Island in mid May the settling basin and piping system were completely cleaned of sediment as an effort to prevent or ameliorate a recurrence. Most of the cabins and other facilities remaining from the fox farming days were demolished by this tidal wave.

Jones' report concerns Adak; Everett (Chap. 8, this volume) gives some evidence of the effects of this tsunami on Amchitka.

At the time of the 1960 Chilean earthquake and resultant tsunami, Jones was on Amchitka. He reports:

A curious event, one that made us uneasy took place on the 23rd and 24th of May [later than the time indicated in Table 5 because of the travel time from South America]. At noon of the former we noted a visible tidal current flowing into the Harbor. Thoughts of a damaging tidal wave leapt to mind and we watched with anxious eyes, expecting a bore to develop. The current oscillated in and out and we thought it prudent

to haul the dory higher on the Island. This we did and continued to watch with apprehension the silent ebb and flow. Clearly the sea was in a state of unrest due to some seismic disturbance. Later we learned of a damaging earthquake at that time on the coast of Chile in South America (Jones, 1960, p. 20).

The Great Alaskan or Good Friday earthquake of Mar. 27, 1964, produced a tsunami that was very destructive in the epicentral region and along the Pacific coast as far as California, but, because of the directionality of the source, the resulting tsunami was little felt in the Aleutians.

No one was on Amchitka on Feb. 4, 1965, when the magnitude 7¾ Rat Island earthquake took place with its epicenter just 20 miles south of Amchitka. This was during the period leading up to Long Shot (below), and so a party was sent to see what damage had been caused on the island. Gard (1965, p. 4) reports that a water wave had washed up on the beaches, "no higher than about 6 feet above high tide," and that the fill land along the foot of Fox Runway had settled (Fig. 4), but no major damage was done.

ACTIVITIES LEADING UP TO THE AEC USE OF AMCHITKA

The western Aleutians must have cropped up numerous times in the postwar years as possible sites for projects requiring isolation from masses of people. I have in my files, for instance, a short memo written in 1960, during the days of great optimism in the Plowshare program,* that discusses the feasibility of using nuclear explosives to dig a harbor at Shemya. It was just a paper exercise, one among many such that were not taken seriously and not followed up on.

Early Site-Selection Efforts

The period of the early 1960s was one of many searches for test sites. During these years limitations began to become evident in the use of the existing Nevada Test Site (NTS). After the unofficial moratorium on nuclear testing was broken by the U.S.S.R. on Sept. 1, 1961, the NTS had been used almost exclusively for underground tests. The city of Las Vegas, 60 miles from Yucca Flat, was beginning to acquire high-rise structures along the "strip." High-rise buildings tend to be sensitive, one might almost say near-resonant, to the ground shocks from the larger nuclear explosions. The initial step in adjusting to this growing problem was to enlarge the test site to the northwest to

*Plowshare was the AEC program of study of non-military uses of nuclear explosions.

Table 5—Tsunamis in the Western Aleutians*

Date (GMT)	Earthquake source	Magnitude	Runup height (m) at		
			Attu	Adak	Unalaska
Dec. 7, 1944	Japan	8.0	0.3	0.1	
Mar. 4, 1952	Japan	8.3	0.1	0.2	0.1
Nov. 5, 1952	Kamchatka	8¼	1.5	1.1	0.6
Nov. 26, 1953	Japan	8.0	0.2		
Mar. 30, 1956	Kamchatka	NA	0.3	0.1	0.1
Mar. 9, 1957	Unimak	8.3	0.6	4.0	0.7
Nov. 7, 1958	S. Kurile	8.7	0.2	<0.1	
Nov. 13, 1958	S. Kurile	7.3	0.2	<0.1	
May 4, 1959	N. Kurile	8	0.2		
May 22, 1960	Chile	8.5	>1.8	1.5	0.8
Dec. 20, 1962	Fox Island	6.5		0.1?	
Mar. 27, 1964	Prince William Sound	8.4	0.4	0.3	0.4
Feb. 3, 1965†	Rat Island	7.75	3.2	NA	0.2
Mar. 29, 1965	Rat Island	7.3	0.2		
Oct. 17, 1966	Peru	7.5	0.1	0.1	

*Source: Cox and Pararas-Carayannis (1969).

†Time was 0521, February 4, GMT, which was 1821, February 3, local time (BST).

include Pahute Mesa, which raised the distance to Las Vegas to over 100 miles. In subsequent years the use of Pahute Mesa has permitted tests of somewhat larger than a megaton at the NTS.

These limitations led in 1964 to an extensive search for an alternative to the NTS. This search was confined to areas in the 48 contiguous states west of the Cordilleran front and turned out to be a mere paper study; no visits to possible sites were permitted, and the 1964 alternate test site efforts died away without ever being formally canceled.

Long Shot

In late 1963 planning started in secret for what is now known as Long Shot. At that time there were unanswered questions about the ability of the U. S. detection system and the worldwide seismic community to detect and distinguish nuclear explosions, especially if one happened to be fired in the Kuriles or in Kamchatka, naturally seismic areas next to the sea. Could an explosion in such a place be distinguished from natural seismic shocks? To what extent would the Aleutian trench, a major exception to the usual seismic assumption of a horizontally uniform earth, speed up or delay a signal and cause its epicenter to be mislocated? It was proposed to shoot an underground nuclear test in that region unannounced and see how the seismic community would do (Test Command, Defense Atomic Support Agency, 1967).

However, the AEC's statutory responsibility for test safety included even those tests carried out by the Department of Defense, and the AEC had to be brought into the planning. The then manager

of the AEC's Nevada Operations Office, James Reeves, insisted that it is just not possible in American society to carry out such a test without knowledge of its preparation leaking out. So the secrecy was dropped and with it the feature of an unannounced seismic event, but the test went ahead on the issue of determining travel times from sources near oceanic trenches. Thus was born Long Shot. Jones (1965, p. 35) confirms the misgivings about being able to keep such a test secret, saying, "In March 1964 we learned of a major, highly classified project soon to begin on Amchitka, and assumed we were again in the presence of the Bomb In the spring a series of heavily loaded military aircraft flights proceeded to Amchitka, and the nature of the cargo (which became common knowledge along the route) confirmed our assumption." The cargo included a Canadian-made drilling rig whose presence became known when the U. S. customs held up its passage through Anchorage some hours for lack of proper papers.

During the summer of 1964, six test holes were drilled about the eventual Long Shot site to confirm the Geological Survey's analysis that there was no local faulting. Preparation for even a simple test is not short, and on Oct. 29, 1965, Long Shot was finally detonated. It was an 80-kt shot 720 m (2350 ft) deep 2 km southwest of Cyril Cove (Chap. 1, Fig. 11).

From the refuge viewpoint, Long Shot was an unexplained interference with the long-term plans for Amchitka by men insensitive to refuge values. Kenyon (1966), in his internal report on the shot, speaks several times about the "progressive destruc-

tion of refuge values that are added by each new invading activity." He mentions meeting men on the project who had no idea before coming that the island was part of a National Wildlife Refuge. Normally a happy man, he was dismayed that he and Spencer, the Associate Supervisor of Alaska Refuges, had to "join, as temporary employees, the staff of the Laboratory of Radiation Biology of the University of Washington in order to make post-blast examination of refuge wildlife resources at Amchitka."

What Long Shot and the two later nuclear shots did to these wildlife resources is discussed in Chap. 26 of this volume. Suffice it to say here that the blast-caused effects of Long Shot were almost nil, but there resulted a small (and still continuing) tritium leak into drilling mud pits next to the Long Shot pad (see Seymour and Nelson, Chap. 24, this volume). The island was evacuated in December 1965, with little effort having been made to clean up the island.

Search for a Supplemental Test Site

In mid-1966 the search for another test site was revived, this time impelled by the need for a place to test a series of devices leading up to the warhead for the U. S. Anti-Intercontinental Ballistic Missile (AICBM) system, which would include yields considerably greater than what experience since 1963 had indicated could be tolerated at the NTS's Pahute Mesa. (The NTS limitation continued to be high-rise structures in Las Vegas, whose numbers and heights were steadily increasing.) The investigation proceeded informally from June until Nov. 18, 1966, at which time a new Site Selection Committee was formally set up. The search had by then narrowed down to an area in central Nevada north-northeast of the NTS and to Amchitka Island in the Aleutian chain, with the western end of the north slope of the Brooks Range in Alaska considered an "insurance" alternative in the event the other sites did not meet programmatic requirements.

Much of the early thinking of this Site Selection Committee was devoted to central Nevada. Eventually a general location in Hot Creek Valley was chosen; particular sites within it were suggested by the Geological Survey; exploratory holes were drilled; and, after the long process of preparation, on Jan. 19, 1968, a calibration shot called Faultless was fired. It was an intermediate yield shot (200 to 1000 kt) at a depth of 975 m (3200 ft). No further work has been done at the Central Nevada Supplemental Test Site. The site is not suitable for shots as large as were required to test the AICBM warhead.

Amchitka

Between Nov. 30 and Dec. 16, 1966, a U. S. Geological Survey team made a geological reconnaissance and aeromagnetic survey of most of the southeastern half of Amchitka. Their immediate purpose was to select five sites for deep exploratory drill holes. They picked five, plus one alternate location, and reported their findings to the Site Selection Committee on Mar. 2, 1967. (Unimaginatively, these six sites were called Sites A, B, C, D, E, and F.) A generalization of their geological findings during this reconnaissance together with data gathered earlier is given in Carr, Gard, and Quinlivan (1967).

The following criteria were used by the Site Selection Committee in its 1966–1967 site-selection activities: The rock needed to be competent enough for mining at shot depth and impermeable enough to avoid the risk of groundwater contamination, all at a depth sufficient for containment of radioactivity. (Amchitka's isolation would help if containment were to fail.) There should be adequate separation of individual sites on the island; sites were to be 4 miles apart, 3000 ft from either coast, and at least 3 miles from Baker Runway. Logistical factors favoring Amchitka were year-round access by sea or air, an existing road network, a harbor, airstrips, and a land mass large enough that people at a Control Point at the northwest end of the island would be far enough from any prospective firing site to protect them from the effects of ground shock. As to environmental concerns, it was recognized that Amchitka is in the Aleutian Islands National Wildlife Refuge and that operations would have to be carried out with minimum disturbance to the natural environment and wildlife.

It would seem that there ought to be a formal Memorandum of Understanding on record between the AEC and the Department of the Interior on the use of the island, but a search for one has not turned it up. Apparently the AEC's original entry onto the island was based on an informal agreement made in late 1966 between AEC Chairman Seaborg and Secretary of the Interior Udall.

ORGANIZATION OF BIOLOGICAL STUDIES ON AMCHITKA

In 1966 Battelle Columbus Laboratories (BCL) was managing a program of ecological studies in Panama for the AEC and the Atlantic–Pacific Interoceanic Canal Commission associated with the possibility of digging a new canal. They were asked to organize studies at Amchitka as well. Their ideas and plans were discussed with the Fish and Wildlife

Service, first in March 1967 and periodically thereafter. Actual on-island biological studies started in the fall of 1967. These investigations were designed to predict, evaluate, and document the effects on the biota and the environment from the proposed nuclear tests, to recommend measures for minimizing adverse effects, and to predict and evaluate the potential hazards to man that might result from the accidental release of radionuclides to the environment and their subsequent transport to humans via marine food chains.

These broad objectives had to be brought down to the level of specific concerns and particular projects. The first list of specific concerns, agreed to with the Fish and Wildlife Service in 1967, is as follows:

1. Effects on the sea otter population.
2. Transport of radionuclides to man via marine processes.
3. Transport of radionuclides to man via migratory birds.
4. Disturbance of terrestrial habitats.
5. Disturbance of freshwater habitats.

The broad objectives and the specific concerns within them changed somewhat as time went on; for instance, the concern about sea otters changed from an early study of their ability to withstand shock waves in the water to a study of their population distribution and behavior. Also, the early emphasis on radionuclide transport changed to an emphasis on possible physical effects on the environment.

Competent investigators had to be recruited. Some of these came from within the Battelle staff; others were enlisted from the academic community and government laboratories. Later a few investigators entered the program under direct contract with the AEC. Most of the contributors to this book are drawn from this group of investigators.

The Fish and Wildlife Service of the Department of the Interior assigned four men to the Amchitka activities: two refuge-management biologists who were rotated to keep one man on the island at all times to monitor construction activities and otherwise to look out for Interior's interests and two research-oriented men to monitor and participate in the research being carried on. (These latter men, Merrell and Abegglen, are also among the authors of chapters in this volume.)

In April 1967 the Department of the Interior and the AEC agreed that demobilization at the conclusion of the program would include cleanup, removal of all movable material brought onto the island, and demolition of buildings built for the project except for what the Department of the Interior would need for its continuing refuge

responsibilities. In general, the island was to be returned insofar as possible to its condition in 1967 before construction activities started. The debris left from Long Shot was to be cleaned up, but not World War II debris or buildings, except in specific instances along roads: it was believed that many of these wartime remains were so covered with subsequent growth that their removal would entail more damage than benefit.

The story of activities on the island during its use by the AEC is left for later chapters of this book. All people evacuated the island on Sept. 8, 1973, after demobilization and cleanup, and AEC rights of use and control over Amchitka were relinquished on Sept. 18, 1973. Two continuing stipulations remain from the AEC occupancy of the island. The Department of the Interior has been asked to prohibit excavation, drilling, and removal of materials near the surface zeroes of the three nuclear tests that have been executed there, Long Shot, Milrow, and Cannikin. Also, the AEC has asked for visitation rights and use of residual facilities and equipment remaining on Amchitka for scientific parties examining possible long-term consequences of those tests. So far there have been three such return parties, in May and August 1974 and in August 1975 (Kirkwood, 1974; 1975; Nelson, 1975).

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APPENDIX A: THE EXECUTIVE ORDER THAT ESTABLISHED THE
ALEUTIANS AS A RESERVATION AND NOW AS A NATIONAL
WILDLIFE REFUGE*

Executive Order

It is hereby ordered that all islands of the Aleutian chain, Alaska, including Unimak and Sannak Islands on the east, and extending to and including Attu Island on the west, be and the same are hereby reserved and set apart as a preserve and breeding ground for native birds, for the propagation of reindeer and fur bearing animals, and for the encouragement and development of the fisheries. Jurisdiction over the wild birds and game and the propagation of reindeer and fur bearing animals is hereby placed with the Department of Agriculture, and jurisdiction over the fisheries, seals, sea otter, cetaceans and other aquatic species, is placed with the Department of Commerce and Labor.

It is unlawful for any person to kill any otter, mink, marten, sable or fur seal, or other fur bearing animal within the limits of Alaska Territory, except under such regulations as may be prescribed by the Secretary of Commerce and Labor; and it is unlawful for any person to kill any game animals or birds in Alaska or ship such animals or birds out of Alaska except under the provisions of law and under such regulations as may be prescribed by the Secretary of Agriculture.

Within the limits of this reservation it is unlawful for any person to hunt, trap, capture, wilfully disturb, or kill any bird of any kind whatever, or take the eggs of any such bird, except under such rules and regulations as may be prescribed by the Secretary of Agriculture.

Warning is expressly given to all persons not to commit any of the acts herein enumerated and which are prohibited by law.

The establishment of this reservation shall not interfere with the use of the islands for lighthouse, military, or naval purposes, or with the extension of the work of the Bureau of Education on Unalaska and Atka Islands.

This reservation to be known as the Aleutian Islands Reservation.

WM H TAFT

THE WHITE HOUSE,

March 3rd, 1913.

[No. 1733.]

*This Executive order has been retyped verbatim from the original copy.

ALEUTIAN ISLANDS RESERVATION

For Protection of Native Birds the Propagation of Reindeer and Fur Bearing
Animals and the Development of Fisheries

ALASKA

*Embracing the Islands of the Aleutian chain as segregated by broken line
and designated "Aleutian Islands Reservation."*

DEPARTMENT OF THE INTERIOR
GENERAL LAND OFFICE
Fred Dennett Commissioner

APPENDIX B: THE WARTIME MEMORANDUM TO TROOPS ON AMCHITKA THAT CALLED ATTENTION TO ARCHAEOLOGICAL SITES ON THE ISLAND*

R E S T R I C T E D
HEADQUARTERS U. S. TROOPS
APO 986, U. S. Army

MEMORANDUM)

16 June 1943

No. . . . 35)

ARCHEOLOGICAL OPPORTUNITIES, THIS STATION

1. It is the desire of this Headquarters, both from the scientific and recreational standpoints, to encourage the collection and preservation of archeological specimens.

2. The Aleutian Islands contain the buried remains of ancient races, important in the peopling of the New World. The soldiers of this garrison have an unparalleled opportunity to collect and preserve these specimens and thus to contribute materially to Science. The United States Government's Smithsonian Institute is interested in the remains found on this island. For a number of years The Smithsonian Institute sent an expedition to the Aleutian Islands. An officer of this Post, FLT Paul Guggenheim, 444th Signal Battalion, was a member of an expedition in 1937.

3. In order to develop our opportunities to the fullest, it is requested that individuals and organizations, wherever they find specimens (bones and tools, etc.) that are suspected to be of archeological interest, preserve the specimens and notify Lt. Guggenheim through Dispatch 16-R1. The specimen should be turned over to Lt. Guggenheim and all the information that can be given concerning the place found, etc., so that more specimens may be located. Specimens will be sent to The Smithsonian Institute and credit will be given to the discoverer. Any person who now has knowledge of the place where specimens may be found should give the information to Lt. Guggenheim.

4. It is desired that Organization Commanders and all other officers explain the possibilities of this endeavor to their men. With interest and enthusiasm on the part of the officers, much interest will be developed. The recreational advantages are great.

5. Excavations for specimens must be made in a scientific manner so as not to disturb or break up specimens in the ground. In the near future, this Headquarters will publish information as to the scientific manner in which to work a site containing specimens, so that men under the supervision of an officer may themselves engage in excavating work. Until that time, sites that are known to contain specimens should not be disturbed unless required for military reasons; but information as to location of the site should be given to Lt. Guggenheim (Dispatch 16-R1). This Headquarters will authorize sites for excavation which will not be disturbed by personnel other than those specifically authorized. Signs will be respected by all personnel.

By command of Brigadier General JONES:

Arthur A. Lundin
ARTHUR A. LUNDIN,
Major, F. A.,
Adjutant.

/jgl
DISTRIBUTION "A"

R E S T R I C T E D

*This memorandum has been retyped verbatim from the original copy.

Previous Scientific Investigations, 1867-1967

R. G. Fuller*

Battelle Columbus Laboratories,
Las Vegas, Nevada

During the first century after the United States acquired Alaska, progress in the scientific exploration of the western Aleutians was erratic. The islands were distant from the Alaskan mainland, and the Aleutian climate was a deterrent to exploration. Despite these obstacles, many investigators were drawn to the remote islands. Between 1867 and 1967

much was learned about the natural history of the western Aleutians and about the primitive peoples who inhabited the islands from prehistoric times. This body of knowledge was a useful base for planning the bioenvironmental studies reported in this volume.

During the first 126 years following the discovery of the Aleutians by Vitus Bering in 1741, some useful information about the geography, human inhabitants, flora and fauna, and general character of the western Aleutians† was collected and recorded by various explorers, by the Russian fur hunters, and by Russian administrators and missionaries who accompanied the hunters and traders during their exploitation of the natives and the natural resources of the islands. But, however valuable these observations may have been, most information was collected only incidentally to the primary missions of conquest, commercial exploitation, and religious conversion that engaged the observers.

Sherwood (1967) reviews the more important investigations of this period, for which he says he "... used the standard sources in English and in German, and in English and German translations from the Russian." I am not surprised that the Aleutians are scarcely mentioned in this review. Most exploring and collecting expeditions bypassed the western Aleutians, concentrating on the mainland, the Alaskan peninsula, and the eastern islands. The Russian center of power for trade and administration, after the first few years of free-for-all exploitation, was located first on Kodiak Island and later at Sitka on Baranof Island. The scattered islands to the west must have been even more forbidding and difficult of access to the early explorers than they were to later investigators.

The discussion that follows will focus on those investigations of a more strictly scientific nature

which began after Alaska was purchased by the United States in 1867. I have chosen to treat the advances in chronological order rather than by scientific discipline. Many of the investigators who have added to our knowledge of the Aleutians were generalists whose interests ranged widely. It therefore seems more logical to discuss their contributions in the order in which they were made,* instead of separating them among different areas of interest. The history of geographic exploration is outside the scope of this chapter; for a good general survey that covers such exploration in the North Pacific Ocean—Bering Sea region up to the early 1960s, see Friis (1967).

The progress of scientific discovery in the western Aleutians after 1867 was erratic and for good reasons. Two themes are common to the accounts of most investigators: (1) the obstacles imposed by adverse weather and (2) the difficulties of getting logistic support and transportation among the remote islands.

Armstrong (Chap. 4, this volume) discusses the Aleutian climate, and the subject needs only brief mention here. Problems that weather posed for field investigators on the foggy windswept islands are easily imagined: it was difficult, and sometimes impossible, to preserve supplies and specimen collections against the dampness; favorable conditions for observing wildlife were rare, and the severe storms that often swept the islands sometimes stopped field work entirely.

*Present address: Oracle, Arizona.

†The Andreanof, Delarof, Rat, and Near Island groups.

*This plan is adhered to except for the treatment of Russian research in oceanography and marine biology. That subject is discussed briefly in a section at the end of this chapter.

Transport was the other big obstacle. Attu Island, at the western end of the chain, is over 900 km (about 550 miles) from Atka. This section of the Aleutians comprises some 40 islands and islets, many of which lack safe harborage for support vessels. The usual base from which to explore the chain was Unalaska, some 500 km (350 miles) east of Atka, and until recently no regularly scheduled transport was available among the islands.* Early investigators were forced to provide their own vessels or to depend on the support of trading ships, government vessels, or any other ships of opportunity that happened to sail through the area.

Commercial and government vessels had their assigned missions, which understandably took precedence over rendering assistance to visiting scientists. Few exploring parties were fortunate enough to work from their own support ships; so a catch-as-catch-can mode of travel was normal. Inevitably, investigators experienced frustrating delays, were often unable to visit important target islands, or had their visits cut short by the early departure of a support ship. So it is not surprising that scientific studies in the western Aleutians seem to have proceeded unevenly with long periods when advances were slight. The investigators worked against formidable odds, and what is remarkable is that they succeeded as well as they did against those odds.

DALL

The American naturalist William Healey Dall had a distinguished scientific career in Alaska, a résumé of which is presented by Sherwood (1965). His work in the far northwest began in 1865 when, at the age of 19, he joined the Scientific Corps of the Russian American Telegraph Expedition. I have found no evidence that this assignment took him into the western Aleutians,† but it did establish his reputation as a reliable and productive field naturalist and awakened in him a lifelong interest in Alaska. When he joined the staff of the Coast Survey in 1870, he embarked on a course that

enabled him to make extensive natural-history collections and to pursue ethnological and archaeological investigations in the Aleutians.

Sherwood (1965) says of Dall: "The collections he made in his leisure time were extensive. He sent seven boxes of dry shells, echinoderms, and fossils to Professor [Louis] Agassiz* at the Museum of Comparative Zoology [Harvard University]. Plant specimens were mailed direct to the eminent American botanist, Asa Gray. In one year alone, Dall forwarded twenty-seven boxes and kegs of general zoological and ethnological materials to the Smithsonian." Hultén (1960) credits Dall with making "... fairly good collections..." of plants, which were deposited in the National Herbarium and in Gray Herbarium at Harvard.

Dall (1877a) reported the results of his archaeological and ethnological studies and the conclusions he drew from them in the first volume of *Contributions to North American Ethnology*. One of his three papers in the volume is "On Succession in the Shell-Heaps of the Aleutian Islands." In the introduction to this paper, he explains the circumstances under which he was able to investigate the archaeological remains of the islands: "The notes of which this paper is the result were made while engaged in a hydrographic and geographical reconnaissance of the Aleutian Islands, under the auspices of the United States Coast Survey. They were made at enforced intervals of leisure, occasioned by weather which would not permit the ordinary surveying operations of the party to be carried on, . . ." Considering the limited opportunities Dall had to pursue this effort, it is noteworthy that he was able to collect as much information as he did.

Dall's report on the shell heaps (mounds of debris that constitute the principal repositories of material remains of the prehistoric inhabitants of the western Aleutians) is prefaced by a brief description of the topography of the islands and the flora and fauna of the islands and adjacent seas. He lists the islands, from Unalaska westward, on which shell mounds were observed or reported to exist (a total of eight). Of these, Amchitka Island is discussed at greatest length, and he stresses the abundance of shell heaps on that island, which he took to be evidence of a large resident human population in earlier times.

Dall describes in some detail the methods he used in excavating the heaps, methods that were remarkably sound as judged by modern standards. Turner (1970) mentioned the fact that Dall in his "... excavations at Constantine Harbor employed the principle of stratigraphy—preceding by 50

*Even today commercial air transport is available on a scheduled basis to only a few of the western islands (Adak, Shemya, and Attu) whereas ship transport is available from Adak to Atka.

†In 1865 Dall crossed the Bering Sea on the expedition vessel *Nightingale* with stops at St. Lawrence Island and at two ports on the Siberian coast. The captain of the *Nightingale* was Charles M. Scammon, who a few years later achieved some scientific recognition with publication of *The Marine Mammals of the North-Western Coast of North America* (Scammon, 1874).

*Dall had studied earlier with Professor Agassiz.

years its use by the archaeologist N. C. Nelson."* Dall reported that excavations were carried out on Attu, Amchitka, Adak, and Atka. As an example of the ground plan of a typical shell heap, he includes a sketch of one examined at the head of Constantine Harbor, Amchitka Island (probably RAT3 as reported by Desautels et al., 1970).

The conclusions Dall reached as a consequence of his archaeological investigations in the Aleutians will be discussed only briefly here. What is notable is that some of his judgments, though by no means all of them, have been supported by the much more extensive subsequent studies. Among his generalizations, probably the most important are:

I. That the islands were populated at a very distant period.

II. That the population entered the chain from the eastward.

III. That they were, when they first settled on the islands, in a very different condition from that in which they were found by the first civilized travelers

VI. That a gradual progression from the low Innuist stage to the present Aleut condition,† without serious interruption, is plainly indicated by the materials of, and utensils in, the shell-heaps of the islands

VIII. That the stratification of the shell-heaps show a tolerably uniform division into three stages, characterized by the food which formed their staple of subsistence and by the weapons for obtaining, and utensils for preparing this food, as found in the separate strata; these stages being

I. The Littoral Period, represented by the Echinus Layer.

II. The Fishing Period, represented by the Fish-bone Layer.

III. The Hunting Period, represented by the Mammalian Layer.

Finally, Dall concludes, "On the whole, I am inclined to think that three thousand years is a moderate estimate for the time required to form these mounds of refuse."

Later workers have challenged Dall's neat division of Aleutian prehistory into the "Littoral," "Fishing," and "Hunting" periods as well as some of his interpretations of cultural evolution among the prehistoric peoples of the chain (Jochelson, 1925; Hrdlička, 1945; Laughlin, 1951; Spaulding, 1953). On balance Dall appears to have reached some sound conclusions regarding the prehistory of the Aleuts, a notable achievement when we consider the hardships and limitations under which he worked.

*Ceram (1971) reports that as early as 1781 Thomas Jefferson described the use of this valuable technique in his excavation of prehistoric earthen burial mounds in Virginia.

†Dall here no doubt refers to the conditions of the Aleuts at the time of first contact with so-called civilized man.

In discussing articles of personal ornamentation found in the shell heaps, Dall notes that the early peoples made beads of amber, among other materials. He adds, "This substance occurs sparingly in the lignitic deposits of Tanaga, Unalashka (sic), Atka, and Amchitka, and was reckoned of the greatest value by the Aleuts." His reference to "lignitic deposits" calls to mind the later discovery of partially carbonized tree remains on Amchitka (Powers et al., 1960; Humphrey and Branstetter, 1973; Barr, Ellis, and Helle, 1973).

Dall (1877b) attempted to determine the relationship between the Aleuts and the aborigines of mainland Alaska, with whom he had been in contact during his early Alaskan field work. He recognized the affinities between Aleuts and Eskimos, on the bases of language, geographic distribution, and a common dependence on maritime resources for subsistence. He listed 20 divisions of Eskimos or Innuist, drawing on his personal observations of those groups occupying the coast of western Alaska and on reports by others on more-distant divisions. The Aleuts were treated in less detail since he had less information to draw on. He recognized two principal geographic divisions: the Eastern or Unalashkans (sic) and the Western or Atkans. He estimated the total Aleut population in 1871 to be about 2450 persons, of whom less than 500 lived in the western islands.

A review in detail of Dall's contributions to knowledge of the geography and natural history of the western Aleutians is beyond the scope of this chapter; they appear to have been substantial by any standard. Bartsch, Rehder, and Shields (1947) give an account of Dall's entire career and a bibliography of his voluminous publications. These authors, staff members of the U. S. National Museum, write:

At the close of the 1874 season Dall was recalled to the Washington office [of the Coast Survey, later the Coast and Geodetic Survey] to assemble all the known data of use to navigation in Alaskan waters. The information thus assembled was published in the 'Pacific Coast Pilot of Alaska,' the foundation upon which all subsequent Alaskan studies by the Coast and Geodetic Survey were based. . . . During his period of office at the United States Coast and Geodetic Survey his spare hours were devoted to the arranging of the immense collections that he had made in Alaskan waters as well as the material that had accumulated at the Smithsonian Institution. His journals reveal that no opportunity was missed to collect on land or with dredge in the sea during his work in the north. Our knowledge of the fauna of that region is still largely based on Dall's collecting.*

*Although this last assertion (made less than 30 years ago!) may be something of an overstatement today, it suggests the esteem in which Dall's work was held by his peers three-quarters of a century after he began his Alaskan field studies.

Dall's primary fields of inquiry were malacology and paleontology, but he was a true naturalist, and his observations and collections ranged far beyond his own areas of special interest into every aspect of natural history. As a result, specialists in many diverse fields benefited from the collections he made. For example, much of our early knowledge of the marine fauna of the western Aleutians rested on the collections made there by Dall during his Coast Survey cruises.

BEAN

Tarleton H. Bean of the U. S. National Museum participated in at least a portion of the 1880 summer cruise of the U. S. Coast Survey vessel *Yukon* commanded by W. H. Dall. The following year he published what appears to be the first attempt to enumerate the fishes of Alaska and adjacent marine waters (Bean, 1881). Bean's list contained 116 species, of which only 16 were collected from the western Aleutians; it represented all the Alaska collections then held by the U. S. National Museum plus a few species that had been reported from Alaska waters by other investigators.* In an Appendix are listed an additional 99 species of fish that "... are known to occur in waters bordering upon the limits of Alaska, and will doubtless be found by future investigations."

A review of the Alaskan species enumerated by Bean shows that nearly all those reported from the western islands were collected by Dall. Amchitka was among the collection locations cited for 10 of the 16 species from the western Aleutians.

TURNER

Lucien McShan Turner, a naturalist, served in Alaska as a meteorological observer with the U. S. Army Signal Corps from 1874 to 1881. In May 1874 he arrived at St. Michael, on Norton Sound, where he was stationed until July 1877. After his return to the States and a brief separation from the Signal Service, he returned to Alaska in May 1878 and began his tour of duty in the Aleutians, an assignment that took him to the western islands of the chain. Turner established and operated a meteorological station on Atka from May through August 1879 and one on Attu from July 1880 through mid-May 1881. His official duties as a weather observer occupied much of his time, but

*Bean says of his listing: "The species named are almost wholly shore species, or such as are found in comparatively shallow water; the deep-water fishes of Alaska are still undiscovered. . . ."

he, nevertheless, managed to make observations and substantial collections of Aleutian birds (his special area of interest), fishes, and mammals and to record some interesting ethnological notes on the Aleuts of the western islands. Turner never maintained a station on Amchitka, but he apparently managed to spend the latter part of May and the early part of June 1881 on that island while he was en route from Attu to Unalaska via schooner.* While there he added considerably to his observations of the natural history of the islands. After Turner returned to the States, he worked up his Alaskan material for publication.

Turner (1886) devoted most of his report to the birds and fishes of Alaska, often supplementing the results of his own investigations with those of others in such a way that it is not always possible to identify the source of the information. Among the fishes he reports as occurring in the western Aleutian region are 11 species not listed from that area by Bean (1881).

Turner appears to have been the first investigator to publish an annotated list of the birds of Alaska. His listing includes over 50 species from the western Aleutian Islands. Over 20 of these species are specifically noted as having been observed on Amchitka. Turner also commented on the adverse effects of native foxes on the breeding populations of Aleutian Canada geese on those islands where foxes occur naturally. His observations thus appear to have anticipated the disappearance of breeding populations of geese from islands to which foxes were introduced in the 1920s.

Turner tried to make plant collections during his stay in the Aleutians, but his attempts were largely thwarted by the weather. He reports that, "... of all great difficulties the most troublesome was to preserve the plants after I had collected them. The constant moisture of the climate has frequently ruined my entire collection of a summer's work." Hultén (1960) notes that Turner left "medium sized collections" in the National Herbarium and Gray Herbarium. However, Hultén is critical of Turner's contribution to the knowledge of Aleutian flora. He points out that, since Turner was not a botanist, his observations regarding the distribution of plants in the Aleutians are not wholly reliable.

EVERMANN AND GOLDSBOROUGH

In 1903 a special commission appointed by the U. S. Commissioner of Fisheries carried out an

*This can be inferred from references to Amchitka observations mentioned in his published report.

investigation of the salmon fisheries of Alaska and, in the course of the study, added considerably to knowledge of the fish fauna of the North Pacific Ocean and the Bering Sea. Evermann and Goldsborough (1907) incorporated this information into a new catalog of "The Fishes of Alaska."* The listing includes more than twice as many Alaskan species as Bean (1881) reported, but the authors rely to a considerable extent on the reports of Bean (1881) and Turner (1886) for data on the western Aleutian fauna. The catalog includes at least seven species from that area that are not in the earlier listings. These are attributed mainly to collections made during the cruises of the U. S. Fisheries vessel *Albatross* in the 1890s and during the salmon investigations of 1903.

CLARK

A. H. Clark of the U. S. National Museum participated in a long northern cruise of the U. S. Fisheries steamer *Albatross* in 1906. The cruise started from San Francisco, Calif., in April, proceeded north along the coast to the Alaskan peninsula, west through the Aleutian Islands, to the Okhotsk Sea, to Japan, to the Hawaiian Islands, and back to San Francisco in December. The *Albatross* passed close to Amchitka without stopping, but brief stops were made at Atka, Agattu, and Attu [see Gilbert and Burke (later in this chapter) for a reference to the fisheries results of the cruise].

Clark (1907) published an account of 18 new species and 1 new genus of birds from eastern Asia and the Aleutian Islands which included a new subspecies of *Lagopus ruprestris* (Rock Ptarmigan)† from Adak Island, presumably collected during the 1906 cruise of the *Albatross*, although this is not stated. Clark (1911) gives a complete listing of the birds collected or seen during the cruise. Of the 172 species and subspecies listed, 43 are noted as occurring in the western Aleutians (Atka, Agattu, Attu, Semichi, and Kiska are specifically mentioned). Most of them are birds associated with the pelagic and seashore habitats, and most are to be found among the species now known from Amchitka Island (see White, Williamson, and Emison, Chap. 11, this volume).

*The title is not entirely accurate; the 288 species listed include 22 species not found north of Dixon's Entrance. Technically these would not be considered Alaskan species.

†*Lagopus mutus* of current nomenclature (Murie, 1959).

GILBERT AND BURKE

The U. S. Fisheries vessel *Albatross* carried out exploratory fisheries investigations in the northwestern Pacific in the summer of 1906. Gilbert and Burke (1912) reported on the results of this cruise. They note:

On the outward voyage the vessel passed the Aleutian chain, touching at Unalaska, Atka, Agattu, and Attu Islands Shore collecting was carried on in these localities, and some 37 hauls of intermediate net or dredge were made along the route, several of these hauls being highly successful. Rich ground, which would repay thorough investigation, was found on Petrel Bank (north and east of Semisopochnoi Island), [and] in the vicinity of Attu and Agattu Islands

These authors concluded that the *Albatross* reconnaissance produced no evidence of a sharply defined marine faunal break anywhere along the Aleutian chain or, in fact, between the Aleutian and Commander Islands. They did note differences between the marine fauna off Kamchatka vs. that around the Commander Islands, which they attribute to the barrier effect of the deep channel between the two areas.

Of the 123 species listed from the 1906 *Albatross* collections, 34 are described as new species (8 new genera are also recognized). Sixty of the species listed are noted as occurring in the western Aleutians if the Petrel Bank collections are included. Among these are 17 of the species described as new.

JOCHELSON

Russian scientific interest in the Aleutians did not terminate with the sale of Alaska to the United States in 1867. Russian scientists continued to inquire into possible geological, floristic, and faunistic relationships among the western Aleutians, the Commander Islands, the adjacent Siberian mainland (especially the Kamchatka peninsula) and the Kurile Islands. The origin and the prehistoric antecedents of the Aleuts also constituted a problem of great interest to the Russians, understandably so because they were the first Europeans to meet and observe the Aleutian aborigines.

The Kamchatka Expedition (sometimes referred to as the Aleut-Kamchatka Expedition) was initiated in 1907 by a Russian banker, F. P. Riaboushinsky, and was later carried out under the auspices of the Imperial Russian Geographical Society. The expedition included 20 scientific staff members and was organized under several divisions representing the disciplines of anthropology, botany, zoology, geology, and meteorology. The

anthropology* division, headed by Waldemar Jochelson, contributed most to our knowledge of the western Aleutians.

Jochelson and his wife, a medical doctor who assisted him in the field work, reached the Aleutians by way of New York, Washington, D. C., San Francisco, and Seattle. En route, official permits were obtained, supplies were purchased and packed for shipment, and Aleutian Island collections in the United States were studied. Transportation for Jochelson's party from Seattle to Unalaska, to various other Aleutian Islands, to the Pribilofs, and, finally to Kamchatka was provided by the Alaska Commercial Company, various U. S. Government agencies, and a Russian military transport. Jochelson and his party apparently had the wholehearted cooperation of almost everyone they encountered, but the uncertainties of travel arrangements and the exigencies of Aleutian weather hampered their field studies and extended the time they spent in the islands well beyond what they had originally scheduled.

Jochelson (1925) writes, "... according to the estimate of our original plans, only one year was to be devoted to the Aleut problem. Actually, the field-work in the Aleutians stretched over a period of 19 months,† while the journey from Petrograd to Unalaska and the preparatory work occupied 3 months more." He also reports: "In all, we excavated at 13 ancient village sites, investigated 57 pits of various size, 3 burial caves, and 3 other caves Of the 47 days devoted to excavation, only 8 were dry and calm; the remainder of the time we worked in rainy and stormy weather"

Jochelson apparently made no excavations on Amchitka, but he did work on Atka and on Attu, westernmost of the Aleutian Islands. He collected much ethnographic data and an extensive Aleut vocabulary, including Aleut terms for many of the important plants and animals which the natives used. He also recorded meteorological observations (maximum and minimum temperatures), and Hultén (1960) credits the expedition with making a small collection of plants, later deposited in Leningrad.

The full report of the findings of the Anthropological Division was published in 1925 under the auspices of the Carnegie Institution of Washington. Jochelson (1925) reports that the original manuscript, written in Russian, was ready for the printer in 1916. Publication was delayed by World War I and the Russian Revolution. Ultimately, Jochelson

brought his manuscript to America, and, after making further comparative studies of Eskimo-Aleut collections in this country, he rewrote it in English. The history, ethnology, and physical anthropology of the Aleuts are discussed in Jochelson (1933).

In his 1925 report, Jochelson discusses at some length the conclusions reached earlier by Dall, who had excavated on some of the same western islands as Jochelson (Attu and Atka). In particular, he takes exception to Dall's division of Aleut culture history into three periods (Littoral, Fishing, and Hunting) and to Dall's contention that the first peoples reaching the islands possessed only a rudimentary culture, lacking fire, stone implements, and many other traits known to the Aleuts at first contact with Europeans.

On the other hand, Jochelson agrees fully with Dall on the important point that the Aleutians were peopled from the east, i.e., from the continent of North America. And, although he is cautious in attempting to fix a date for the first habitation of the islands, his judgment is not greatly different from that of Dall. Jochelson concludes: "All the foregoing considerations fail to give us a definite measure of time which could be expressed in figures; nevertheless they show clearly that the Aleut came to the islands many centuries ago" His "... many centuries . . ." can easily accommodate the 3000 years cited by Dall as a reasonable estimate for the time required to form the shell heaps he excavated.

BENT ET AL.

A. C. Bent, R. H. Beck, F. B. McKechnie, and A. Wetmore participated in a brief natural-history survey of some of the western Aleutian Islands in 1911, and Bent (1912) reported the observations of avifauna made during the expedition. Bent's paper indicates that the original plans called for chartering a special vessel and for spending "... the entire summer in making a thorough biological survey of the whole Aleutian chain" So much for plans; this scheme was subsequently abandoned, and the party finally accepted transportation aboard the U. S. Treasury Department revenue cutter *Tahoma*. Consequently the investigators settled for a greatly reduced field program; Bent (1912) writes, with obvious disappointment, "... we started (from Unalaska) on the western trip among the Aleutian Islands on June 10, with orders for the *Tahoma* to return to Unalaska on July 1. This gave us less than three weeks to explore over 800 miles of difficult islands, an undertaking for which three months would have

*Also sometimes referred to by Jochelson (1925) as the ethnological division.

†January 1909 to July 1910.

been hardly enough." The expedition members landed briefly on Atka, Adak, Tanaga, Kiska, and Attu but were unable to explore any of these islands thoroughly. Most of their efforts seem to have been concerned with observations of avifauna and collection of bird specimens. However, Hultén (1960) notes that Wetmore also made plant collections at Atka, Kiska, Attu, and Tanaga; these collections were later deposited in the U. S. National Herbarium.

Bent (1912) reports: "Good series of all the land birds were collected on nearly all of the islands visited; particularly fine series of the various subspecies of ptarmigan were taken, . . . among which a new subspecies was discovered inhabiting Tanaga Island, *Lagopus ruprestris sanfordi*;* two species, hitherto unrecorded from North America, were collected, . . ." Of the 62 species and subspecies listed by Bent, 35 are specifically identified with western islands.

TATEWAKI AND KOBAYASHI

The Japanese botanist Misao Tatewaki, accompanied by an assistant, visited the middle and western Aleutians briefly in the early summer of 1929, at which time they collected plants on Attu, Amchitka, and Atka. In 1931 Yoshio Kobayashi spent 3 months among the Aleutian and Commander Islands collecting on Attu, Amchitka, Atka, Umnak, Unalaska, and Bering Islands. Kobayashi's visit was made possible by the support of a Japanese newspaper company; it is a matter of some curiosity that such a company took an interest in the flora of the Aleutian Islands at that time.†

Tatewaki and Kobayashi (1934) jointly published the results of their botanical explorations in the islands. In addition to their catalog of the terrestrial plant species, they also attempted to characterize the plant associations of the islands, starting with the marine plants of the "Sublittoral Belt," which they define as being "a few metres in depth at the low tide." These authors identify several marine algal associations that have been recognized in more recent studies of the inshore

marine flora of the islands and also note the common terrestrial associations. The catalog of Aleutian flora by Tatewaki and Kobayashi (1934), coupled with publications regarding special plant groups based on their collections (Akiyama, 1933; Satake, 1932; Okamura, 1933), constituted the most complete description of the plants of the Aleutian chain available before the publication of the monograph by Hultén (see below). Over 300 species of terrestrial plants are listed, and, of these, 106 were reported as having been collected on Amchitka, although not necessarily on that island alone.

HULTÉN AND EYERDAM

The first comprehensive treatise on the vascular flora of the Aleutians was published in 1937 by the Swedish botanist Eric Hultén. A revised and enlarged second edition of this work was published in 1960. In the preface to the first edition, Hultén explained why he felt it necessary to carry out his extensive collecting trip through the islands in 1932. In 1930, after publishing a work on the flora of Kamchatka, Hultén undertook a study of the phytogeography of the Bering Sea region. He soon concluded that the flora of the Aleutian Islands "... was so little known that practically nothing could be said with any certainty concerning the occurrence and distribution of the plants of the islands. This was particularly true of the western part of the chain . . ."

Having recognized the need for more information on the Aleutian flora, Hultén set out to obtain it. He collected in the islands in the summer of 1932 in company with an American associate, W. J. Eyerdam. The expedition was supported financially by Swedish scientific groups, including the Swedish Academy of Science. Working out of Unalaska as a base, Hultén and Eyerdam made two collecting trips through the islands, one aboard a trading ship belonging to the Alaska Commercial Company and the other in the U. S. revenue cutter *Haida*.

Hultén (1960) gives a serial account of plant collections made in the Aleutians through 1951. His listing covers a period of over 170 years (1779 to 1951). For that period Hultén lists 27 instances of collections made in the western Aleutians, including his own. His samplings in the western islands were made at Atka, Adak, Rat, Attu, Alaid, Agattu, Kiska, Kanaga, and Amchitka Islands. Collections on Amchitka were made at two locations, "... one close to 'Square Bluff' of the marine chart, the other in the middle of the northern shore . . ." At least 9 of the 27 western

**L. mutus* in current nomenclature.

†An American official who saw Japanese at Amchitka and on other islands in the summer of 1931 conjectured much later that the visitors may have been spies, although their ostensible purpose was to maintain emergency caches of fuel and supplies in support of a "Tokyo-San Francisco Good Will Flight," the route of which was over the Aleutians (Dufresne, 1966). There is no indication as to whether the botanist Kobayashi was one of the three Japanese Dufresne saw at a distance in Constantine Harbor in 1931.

Aleutian collections mentioned in his serial list involve Amchitka.

In preparing the second edition of his work on Aleutian flora, Hultén not only used his own extensive collections but also had access to the holdings of the more important herbaria of the world, including several in the United States. Hultén presented a complete list of the vascular plants then known to occur in the Aleutians as well as his analysis of the phytogeography of the chain and the affinities of the island flora with those of the adjacent Asian and North American mainlands. Subsequent collections have shown that Hultén's list was not complete and that his assumptions regarding distribution of species among the islands were not always entirely correct. Shacklette et al. (1969), who made collections on Amchitka in 1966 to 1968, list 2 species of vascular plants previously unreported from the Aleutians and 47 species heretofore unreported from Amchitka. Shacklette et al. also list a number of lower plant species not previously reported from the islands.

In general, Hultén's conclusions regarding the major features of the Aleutian flora are still considered valid despite the subsequent accumulation of some new information regarding species distribution. He pointed out that the island flora, particularly that of the western section of the chain, has much stronger affinities with Kamchatkan flora than with that of the North American mainland. He also noted the depauperate character of the Aleutian flora and emphasized the relative instability of plant associations in the Aleutians as compared to their counterparts on Kamchatka.

The Hultén-Eyderdam expedition also produced one of the earliest published reports indicating the recovery of the once-threatened sea otter population in the western Aleutians. Eyderdam (1933) notes: "In July 1932, while engaged in botanical explorations on various islands of the Aleutian chain, I spent two weeks on Atka Island, and there learned that sea otters are becoming quite common in the Western Aleutians." Eyderdam went on to suggest that it would be desirable for "... our government to capture a couple of dozen pairs to transplant at the Pribilofs or at some favorable locality where they can be guaranteed full protection."

HUTCHISON

A British botanist, Isobel Wylie Hutchison, made a brief plant collecting tour through the Aleutians in the summer of 1936 while traveling aboard the U. S. Coast Guard cutter *Chelan*. In the western islands she collected at Atka, Amchitka, Kiska, and Attu. Her collections, which included

about 50 species from Amchitka (Hutchison, 1942), were deposited in the British Museum. An account of her collecting experiences in the Aleutians and a list of the collections are given in Hutchison (1937).

MURIE ET AL.

The first coordinated biological study of the entire Aleutian chain was conducted by the U. S. Bureau of Biological Survey during three consecutive summers, 1936 to 1938. The 1936 expedition, led by Olaus J. Murie, included Cecil S. Williams, also of the Survey, and Homer W. Jewell and H. Douglas Gray of the Alaska Game Commission. The 1937 party, also headed by Murie, included Victor B. Scheffer and John B. Steenis of the Survey and, again, Douglas Gray. Scheffer headed the 1938 expedition, concentrating mainly on the nearshore marine life of the islands; information is lacking as to whether any other scientists accompanied him.

All three expeditions were carried out with the support of the *M. V. Brown Bear*,* which enabled the parties to make the most comprehensive biological reconnaissance of the islands thus far carried out. Murie (1959) says, "During these two seasons (1936-1937) we visited every Aleutian Island of any size, as well as many islands south of the Alaska Peninsula and several points on the Peninsula, . . ." The three expeditions gave some attention to essentially every aspect of the biota of the islands. However, when the official report was ultimately published by the U. S. Fish and Wildlife Service (Murie, 1959), it was entitled "Fauna of the Aleutian Islands and Alaska Peninsula." Plant life got meager notice in the report, discussion being limited to two and a half pages on marine algae.† Hultén (1960) reports that plant collections were made by the *Brown Bear* scientists, and he presumably included the results of these in the second edition of his monograph on the Aleutian flora.

The objective of the *Brown Bear* expeditions was to obtain data needed by the Bureau of Biological Survey for management of the Aleutian Islands Reservation (later the Aleutian Islands

*The *M. V. Brown Bear* was later used to conduct the oceanographic surveys of the Chukchi Sea in 1959 and 1960 in connection with the AEC-supported study of the Cape Thompson Region (Wilimovsky and Wolfe, 1966).

†One marine vascular plant, eel grass (*Zostera* sp.), is mentioned as occurring near Umnak Island "... but was not seen farther west." (Scheffer in Murie, 1959).

National Wildlife Refuge).^{*} As Murie writes in the 1959 report: "In 1920, the United States Bureau of Biological Survey was given the responsibility for enforcement of the Alaska fur laws and administration of the *blue-fox industry* (emphasis added) in the Aleutians. As time went on, it became apparent that proper supervision of this important wildlife refuge would necessitate an extensive inventory of the resources of these islands." It was the purpose of Murie and his colleagues to provide such an inventory.

I have not found a narrative account of the *Brown Bear* expeditions which would indicate just how much of the effort was devoted to the western Aleutians, but there is evidence that the westernmost islands were visited during each of the 3 years involved and that Amchitka Island received a considerable amount of attention.

1936

An unpublished "Report on Amchitka Island," provided from the files of the U. S. Fish and Wildlife Service, Anchorage, Alaska, dated Aug. 11, 1936, and written by H. W. Jewell and H. D. Gray, notes: "The dates of our visits to Amchitka Island are July 24 and August 1, 1936." A review of Murie (1959) reveals, from his comments on various species of avifauna, that the 1936 cruise included, in addition to Amchitka, at least the following other western islands: Adak, Kanaga, Kiska, and Attu. It seems reasonable to assume that some additional islands among the many from Atka westward were visited in 1936.

1937

Another unpublished report provided from the files of the U. S. Fish and Wildlife Service, Anchorage, Alaska, gives the itinerary of the *Brown Bear* party for the 1937 season. In brief, the ship provisioned at Unalaska in late May and then proceeded to Attu with stops at Umnak, Atka, and Kiska. Attu was reached on June 7, and from there the party worked eastward, stopping at some islands not visited in 1936. From July 4 to July 18, Murie was left on Amchitka and Steenis on Kanaga while the *Brown Bear* returned to Unalaska for supplies with Scheffer and Gray remaining aboard to continue their scientific duties. The cruise continued after Murie and Steenis were picked up, the Aleutian work ending in early September at Unimak. From there the party departed for Seattle.

^{*}See Chaps. 6 and 20 of this volume for a history of the administrative permutations experienced by the Reservation or Refuge and changing concepts of management.

1938

Victor B. Scheffer, scientific leader of the 1938 cruise of the *Brown Bear*, contributed a section entitled "Invertebrates and Fishes Collected in the Aleutians, 1936–1938" to the report by Murie. Some inferences concerning the western islands visited during 1938 can be drawn from collection sites and dates given for fish specimens mentioned in his contribution. Scheffer (1959) cites examples of marine and anadromous fish collected at Attu (August 16), Kiska (August 19), and Amchitka (August 22). Apparently the expedition was making its way eastward from the end of the chain in mid-August, and many other western islands were probably visited during this final cruise.

The *Brown Bear* survey of the Aleutians accomplished a great deal, although it is unfortunate that so long a delay occurred before publication of the official report of the expeditions (Murie, 1959). In keeping with the stated purposes of the survey, field studies concentrated on birds and mammals. Voluminous, although unpublished, internal U. S. Fish and Wildlife Service (FWS) reports were made promptly to guide decisions for wildlife management of the many diverse islands of the Refuge; these appear to have served their purpose well.

Other aspects of the island biota were not wholly neglected. Extensive, although by no means exhaustive, collections were made of marine and terrestrial plants; marine, freshwater, and terrestrial invertebrates; and marine and freshwater fishes. The collections were made available to appropriate specialists in the scientific community and formed the basis for a number of separate publications in technical journals (see Bartsch and Rehder, 1939; Clark, 1939; Murie, 1940a, 1940b, 1945; Schultz, 1939).

The following section will show that the *Brown Bear* party of 1936 also made a contribution to the archaeological exploration of the Aleutians, although this endeavor was somewhat tangential to the main purposes of the survey.

HRDLIČKA

While the U. S. Bureau of Biological Survey was investigating the flora and fauna of the Aleutians, a small party from the Smithsonian Institution, led by the physical anthropologist Aleš Hrdlička, was digging into the question of prehistoric human occupation of the islands. Hrdlička's work in the Aleutians, which reached westward to include the Commander Island group, was a natural extension of his earlier studies on the Alaskan mainland and on Kodiak Island. Those

investigations were, in turn, stimulated by his belief (Hrdlička, 1930) that "Alaska and the opposite parts of Asia hold, in all probability, the key to the problem of the peopling of America."

Hrdlička's most extensive field study of the archaeology of mainland Alaska and a concurrent ethnological investigation of Alaskan Indians and Eskimos were carried out in the summer of 1926. His account of this work and the conclusions he reached are given in Hrdlička (1930). In that report he reached no definitive judgment regarding the role of the Aleutian Islands in the "peopling of America" or on the relationship of the Aleuts to other northwestern aborigines. What is somewhat surprising is that he suggests (in Fig. 29 of the 1930 report) the Kamchatka-Commander Islands-Aleutian Islands route as one of several potential pathways for "probable movements of people from northeastern Asia to Alaska . . ." This suggestion is at variance with the conclusions of the earlier archaeological workers in the western islands, Dall and Jochelson; these investigators agreed that the Aleutian chain was occupied by peoples migrating from the east, not from the west.

Ten years after Hrdlička's 1926 anthropological survey of mainland Alaska, he turned his attention to a field study of the Aleutian and Commander Islands. At least as late as the start of the 1936 to 1938 series of expeditions, Hrdlička apparently still entertained the idea of a possible west-to-east human migration route from Asia via the Aleutians with the Commander Islands possibly a part of the pathway.

Hrdlička (1945) gives the most detailed account to that date of Aleutian anthropology as well as a wealth of detail on the early accounts of the Aleuts at time of contact as recorded by Russian and other observers. And, of interest in the present context, he provides a delightfully personal and graphic picture of the day-to-day problems and difficulties of conducting scientific work in the islands. His 1936 to 1938 expeditions were modest in size and almost Spartan in character. Hrdlička relied on volunteers, mainly college students, for help in the field; he worked alongside his assistants, sharing with them the labor and discomforts of excavation and cave exploration, and he relieved the tedium of evenings and periods of forced inaction by giving his student helpers formal lectures on such subjects as "Major Indian Remains and Mounds" and "Domestication of Animals in America." To his self-imposed duties as a scientific leader, laborer, and lecturer, Hrdlička added the further task of cooking for the party; his daily notes sometimes refer to the problems involved in this chore, given the limited range of supplies from which to construct his menus.

The Smithsonian Aleutian expeditions, like those of most earlier investigators, depended for logistic support on the help of the U. S. Government agencies (Coast Guard, Bureau of Biological Survey, and Coast and Geodetic Survey) and on the Alaska Commercial Company. Doubtless this kind of dependence determined to some extent where the expeditions were able to work. But a review of the daily logs for the three seasons indicates that the western islands, including Amchitka, were the scene of a considerable amount of the work.

1936

Hrdlička's party stopped briefly at Atka on July 6 (after spending some time at more easterly sites) and worked at Kiska and Little Kiska from July 7 to 27. On July 25 the Bureau of Biological Survey vessel *Brown Bear* arrived, providing a pleasant diversion that Hrdlička acknowledges in his notes:

They [the *Brown Bear* party] take us out to the staunch, good, new, chubby ship, give us an excellent warm supper, and we spend the rest of the evening in their company. But that is not all. Dr. Murrie (sic) leads me to another part of the boat and there presents me with a sack full of skulls and bones, and another with a mummy, from the hot cave on Kagamil Island . . . This is the first tangible news both as to the location of the cave and its contents, and I am deeply grateful.

1937

The party reached Adak on July 5. The period July 7 to 15 was spent in what proved to be an unproductive visit to the Commander Islands. At Bering Island, Hrdlička encountered so much red-tape obstruction on the part of the Russian administrator that the attempt to do any field work on these islands was given up. The party then returned to Attu, westernmost of the Aleutian Islands, and from July 16 to August 17 divided its efforts among Attu, Agattu, and several islands in the western part of the Andreanof group.

1938

This season's schedule finally enabled Hrdlička to excavate on Amchitka, which he considered to be a site of considerable importance to an understanding of Aleutian prehistory. That year work in the western islands began at Kanaga on June 9. Amchitka was reached on June 12, and Hrdlička notes that three members of the party moved into ". . . a little house just put up there by the Bureau of Fisheries." Others occupied a "native hut." The expedition remained on Amchitka until July 5 and excavated in two sites near the head of Constantine

Harbor (probably Sites 2 and 3 of Desautels et al., 1970). Preparing to leave Amchitka to make another attempt at working in the Commander Islands, Hrdlička noted in his diary: "... will leave with regrets—would have liked to stay here much longer."

This time the visit to the Commander Islands, though brief, accomplished its purpose.* Hrdlička concludes, in summarizing the results of this reconnaissance: "One point alone is now definitely established—the Commander Islands were not a stepping stone in the peopling of America . . ."

One important conclusion Hrdlička reached, on the basis of his three seasons' work in the Aleutians, was that two distinct peoples, of different physical type and with minor cultural differences as well, occupied the islands in sequence. He refers to the older as "pre-Aleut" and the later as "Aleut," distinguishing them mainly on grounds of differences in cephalic index. He believed that some of the earlier pre-Aleuts survived to historic times and also that there had been some mixing of pre-Aleut and Aleut stocks.

Hrdlička (1945) was critical of the conclusions reached earlier by Dall (1877a) and Jochelson (1925) not only because they had failed to recognize what he believed to be a fact (the existence of two distinct prehistoric human populations on the island) but also because they had postulated a somewhat longer human occupation of the Aleutians than Hrdlička considered demonstrable. He concluded that the oldest deposits could all "... fit well within the Christian era." He offers no final judgment regarding the important question as to whether the Aleutian Islands were peopled by migration from the North American mainland or directly from Asia or the Kurile Islands by peoples moving in a west-to-east direction. The nearest he gets to this point is his definite exclusion of the Commander Islands as a possible stopping point along a west-to-east migration route.

Later investigators, including Laughlin† (1951) and Spaulding (1953), question the validity of much of Hrdlička's analysis of Aleutian prehistory, chiefly on the grounds that he ignored the implications of stratigraphic sequence in his excavations

and that he allowed preconceived theoretical notions to overshadow empirical evidence. Nevertheless, his pre-Aleut/Aleut categories persist, in somewhat altered form, in the Paleo-Aleut/Neo-Aleut distinctions recognized by modern anthropologists.

GABRIELSON

During the summer of 1940, Ira N. Gabrielson, then Director of the U. S. Fish and Wildlife Service, traveled through the Aleutians aboard the *Brown Bear* and made extensive ornithological collections. He notes in *The Birds of Alaska* (Gabrielson and Lincoln, 1959) that Amchitka was one of the islands visited on the 1940 cruise. Murie (1944) published a new subspecies of Rock Ptarmigan (*Lagopus mutus gabrielsoni*) which was based on specimens collected by Gabrielson at Amchitka in June 1940.

GUGGENHEIM

The first systematic attempt to identify and map the archaeological sites on Amchitka Island (primarily the shell heaps or middens associated with prehistoric settlements) was made by Paul Guggenheim while he was stationed on the island during World War II. Guggenheim, a medical doctor rather than a professional archaeologist, nevertheless had special qualifications for undertaking this task. As a college student he had been a member of Hrdlička's 1937 expedition and he had retained a keen interest in Aleutian prehistory. More important, from his experience with Hrdlička, he recognized the significance of the information contained in the middens.

Guggenheim (1945) describes his largely unsuccessful attempts to discourage promiscuous and destructive artifact hunting during his 10-month tour of duty on the island (May 1, 1943, to Mar. 6, 1944). Looting of the shell mounds was indulged in alike by officers, enlisted men, and civilians during the military occupation of Amchitka despite Guggenheim's efforts to prevent this. He reports that the military command made some attempts to prevent indiscriminate digging, but these seem not to have been a very effective deterrent. His suggestions that the military occupation be used as an opportunity to support professional archaeological investigations were never taken up.

According to Guggenheim, his own collections, some obtained by digging and some by purchase or as gifts from others, eventually "... found their way into the Smithsonian..."; their scientific value is questionable because of the methods under

*Hrdlička also reports that an interesting side trip was made to a Russian biological station on Copper Island. Alan G. May, one of his assistants, later published a more complete account of this station: "... the only Sea Otter Experimental Station in the world." (May 1943.) Captive sea otters were being maintained in both saltwater and freshwater and were reportedly breeding in captivity.

†W. S. Laughlin was a student member of Hrdlička's 1938 field party.

which they were obtained (see McCartney, Chap. 5, this volume). His contribution to Aleutian archaeology lies in the site inventory he made for Amchitka Island. Although this inventory was not complete, it showed that the island is remarkably rich in identifiable prehistoric sites. Guggenheim showed the location of 49 sites (40 certain and 9 probable) distributed more or less uniformly around the shoreline and on offshore islets. This represents nearly two-thirds of the sites identified in the intensive surveys conducted during recent AEC operations on Amchitka and reported by Desautels et al. (1970). Undoubtedly the reconnaissance and mapping done and reported by Guggenheim facilitated the recent surveys. So, despite the damages sustained by archaeological remains on Amchitka during World War II, some benefits also accrued owing to the fact that one member of the occupying force had earlier been exposed to the influence of Aleš Hrdlička.

SUTTON AND WILSON

Occupation of Attu Island by U. S. military forces during the last years of World War II afforded an opportunity for two American scientists stationed on the island, G. M. Sutton and R. S. Wilson, to make field observations of the avifauna of Attu. Sutton and Wilson (1946) published an annotated list of the winter birds which was based on observations made during the period Feb. 20 to Mar. 18, 1945. Wilson (1948) lists the birds he saw on Attu during the summer of 1945.

The two papers enumerate a total of 35 species: 10 seen only during summer, 11 seen only during winter, and 14 present during both seasons. The lists are, of course, not definitive since the observers were not able to spend much time in the field or to travel over the entire island. With two exceptions all the species listed are included in the latest listing of the birds of Amchitka Island (White et al., Chap. 11, this volume). Sutton and Wilson report sightings of the Gray Sea Eagle and the Herring Gull, but Murie (1959) expresses doubt about the validity of the Gray Sea Eagle sighting. No specimens of either species were collected.

UNITED STATES GEOLOGICAL SURVEY (USGS)

The geology of the western Aleutians was little investigated until relatively recent times. Capps (1934), reporting on his visit to a few of the islands in 1932, cites only four published references, and these appear to deal mainly with the eastern islands and the Alaskan peninsula. Capps, a USGS geolo-

gist, accompanied a U. S. Navy hydrographic reconnaissance made aboard the U.S.S. *Gannett*. He was able to go ashore briefly at Adak, Atka, Kiska, and Attu. His report provides only a preliminary overview of the geology of these islands.

The USGS began a detailed study of the Aleutians in 1946, initially focusing attention on volcanoes that were considered possible threats to U. S. military installations. The genesis of this study, the field portion of which continued through 1952, is described by Kennedy and Waldron (1955): "In October 1945 the War Department (now Department of the Army) requested the Geological Survey to undertake a program of volcano investigations in the Aleutian Islands—Alaska Peninsula area. The first field studies, under general direction of G. D. Robinson, were begun as soon as the weather permitted in the spring of 1946." This reference also mentions the existence of an unpublished USGS report that is based on "... a reconnaissance investigation of the Alaska Peninsula and the Aleutian Islands" made by T. A. Jaggard in 1927.

Field support for the investigations was provided by various branches of the U. S. military forces. In addition, the Geological Survey motor ship *Eider* was used as a base for some of the field operations.

Results of the 1946 to 1952 field studies were published in *Investigations of Alaskan Volcanoes*, U. S. Geological Survey, Bulletin 1028, Parts A—U, and in a number of journal papers. A review of Bulletin 1028 shows that much of the study was devoted to the western Aleutians; the relevant parts of this Bulletin are tabulated in Table 1.

No attempt has been made to identify and list the various other papers that are based on these USGS investigations and published in the technical literature.

PEABODY MUSEUM, HARVARD UNIVERSITY EXPEDITION

An anthropological study in the Aleutians was carried out in 1948 and 1949 under the auspices of the Peabody Museum, Harvard University. Laughlin (1951), writing on Alaskan prehistory and ethnology, refers briefly to the expedition, crediting support for it to the Viking Fund, Inc., and the Office of Naval Research. Details regarding the field investigations have not been found; so how much effort was devoted to the western islands is not clear.

Laughlin, in the reference noted, gives a short résumé of the earlier archaeological and ethnological investigations in the Aleutians, with special

Table 1—Parts of USGS Bulletin 1028 Devoted to Western Aleutians

Subject	Part (Bulletin 1028)	Author and date
Great Sitkin Island	B	Simons and Mathewson (1955)
Northern Adak Island	C	Coats (1956a)
Kanaga Island	D	Coats (1956b)
Some western islands	E	Coats (1956c)
Ocean floor, northeast Rat Islands	G	Snyder (1957)
Little Sitkin Island	H	Snyder (1959)
Delarof and West Andreanof Islands	I	Fraser and Barnett (1959)
Gareloi Island	J	Coats (1959a)
Segula, Davidof, and Khvostof Islands	K	Nelson (1959)
Adak and Kagalaska Islands	M	Fraser and Snyder (1959)
Semisopochnoi Island	O	Coats (1959b)
Amchitka Island	P	Powers, Coats, and Nelson (1960)
Rat Island	Q	Lewis, Nelson, and Powers (1960)
Kiska Island	R	Coats, Nelson, Lewis, and Powers (1961)
Near Islands	U	Gates, Powers, and Wilcox (1971)

emphasis on skeletal remains recovered by Hrdlička and Jochelson. New data are presented on anthropometry and distribution of blood groups among present-day Aleut populations. These, together with linguistic and cultural features, are used as the basis for elucidating relationships between the Aleuts inhabiting the eastern and western parts of the chain and between Aleuts and other Eskimo peoples.

In this paper Laughlin retains the Pre-Aleut and Aleut terminology recognized by Hrdlička. In later papers he and other anthropologists have substituted the terms Paleo- and Neo-Aleut to distinguish the two somewhat different aboriginal stocks that peopled the Aleutians (Spaulding, 1953; Laughlin, 1963).

UNIVERSITY OF MICHIGAN EXPEDITIONS

Ethnobotanical and archaeological studies in the Aleutian Islands, under the auspices of the University of Michigan, were started in 1948. These field investigations were continued for several years thereafter with support from the Office of Naval Research and the Michigan Memorial Phoenix Project. T. P. Bank II, of the University of Michigan, Department of Botany, initiated the

field work and was the author of most of the publications resulting from the project.

In a popular account of the first summer season in the islands, Bank (1956) lists the objectives of the expedition: (1) to "make a complete collection of plants"; (2) "... to explore and map the least known of the islands"; (3) "... to visit the few scattered villages where Aleuts were still living and to record their fast-disappearing native customs, especially those pertaining to old uses of plants for foods, medicines, and poisons"; and (4) "... to compile a manual of useful plants and animals in the Aleutians." The field party during the first season was a modest one: Bank, then a graduate student, and one assistant. They got as far west as Atka, traveling by military ships and aircraft, made plant collections, explored some archaeological sites, and established working relations with Aleut informants.

I have found no comprehensive description of the studies carried out by the University of Michigan expeditions and no evidence that any of the four stated objectives was fully realized. However, in a paper submitted for publication in 1952, Bank (1953a) reported: "In all, four trips have been made to the Aleutians, during which more than 20 islands were visited." In a footnote to this paper, Bank is identified as "Field Director,

University of Michigan Expeditions to the Aleutian Islands, 1948-52," from which it can be inferred that the investigations extended at least over the 5-year period indicated.

Bank (1952) gives a generalized view of the plant communities associated with the topographic features of the two main island types represented in the Aleutians: "mountainous" and "plateau" islands. He also (Bank 1952, 1953a) notes the importance of drainage as a determinant of plant-community type and calls attention to the inherent instability of plant communities in the islands: "The ecological concept of succession is hard to apply to communities which continue to fluctuate in an unstable way so that a so-called climax grouping today may be shown later to have been only temporary." Ethnobotanical findings of the expeditions are given in Bank (1953b, 1953c), which discuss the uses made of plants by the Aleuts and the vegetational cover associated with ancient Aleut village sites.

Spaulding (1962) reported the results of the principal archaeological investigation carried out by the Michigan group in 1949, i.e., excavations in two prehistoric dwelling sites on Agattu Island* near the western end of the chain. An important outcome of this work was the recovery of wood and charcoal samples suitable for radiocarbon dating from the refuse mounds. Charcoal from an intermediate depth in one of the excavations was assigned an age of 1300 ± 150 years. The average age of two wood samples from near the base of the same mound was estimated as 2565 ± 300 years. These findings suggest that the prehistoric peoples reached the western islands at an early time, supporting Dall's estimate made three-quarters of a century earlier.

UNITED STATES FISH AND WILDLIFE SERVICE (FWS)

As World War II ended and military control of the Aleutians was relaxed, the FWS undertook field investigations in some of the islands comprising the Aleutian Islands National Wildlife Refuge. Two subjects, sea otters and birds, received special attention, with principal stress being placed on the former. This emphasis was a natural one.

On the basis of a number of observations, it was known that the once-decimated Aleutian sea otter population had grown to sizeable proportions, especially around some of the western

islands, under the protection initiated in 1911 (Abegglen, Chap. 20, this volume). There was an acute need for more information on sea otter distribution and biology to guide management of the resource. It was also recognized that the Aleutians are an important breeding ground for waterfowl, although fox farming, established earlier on many of the islands, was hardly compatible with successful use of the habitat by nesting birds.

Amchitka Island was a logical choice as a field laboratory for sea otter and avifaunal studies. It had a large sea otter population and was potentially a good breeding habitat for waterfowl. The island had additional advantages as a site for field work: an airstrip, a harbor, and a system of roadways developed by the military.

Between 1949 and 1952, R. D. Jones, Refuge Manager, collected carcasses of a number of dead or moribund sea otters on Amchitka beaches and submitted them to pathologists at the Arctic Public Health Center (then in Anchorage, Alaska) for examination. Rausch and Locker (1951) and Rausch (1953) reported the results of their parasitological studies of these animals. Several internal parasites, at least two of which are pathogenic, were isolated; some parasites were found in most carcasses examined. However, the investigators could not implicate the parasites as a major cause of sea otter mortality at Amchitka. Rausch (1953) hinted that a too high sea otter population density may have been a contributing factor and recommended efforts to redistribute (transplant) sea otters from Amchitka to other suitable habitats.

Early transplant attempts were unsuccessful; captive animals died before they could be removed from the island from causes that were not readily apparent. In 1954 a study of the physiological reactions of captive otters was carried out at Amchitka by investigators from Purdue University assisted by FWS personnel and supported by FWS funding. The results of this study were reported by Kirkpatrick, Stullken, and Jones (1955) and Stullken and Kirkpatrick (1955). The conclusion was that captive sea otters generally died from the combined effects of inadequate (too infrequent) feeding and environmental stress. Some progress was made in maintaining animals in captivity for long periods, but the problems involved in transplanting were not entirely solved.

One FWS staff member who collaborated with the Purdue investigators was Calvin J. Lensink, who went on to conduct an intensive study of the status and distribution of the sea otter in Alaska. The findings of this investigation, reported by Lensink (1960, 1962), established the fact that northern sea otter stocks, nearly wiped out before 1911, had increased substantially after protection

*Aleš Hrdlička excavated sites on Agattu in 1937 but at a location several miles from the Krugloi Point sites where the Michigan party worked.

was imposed. Lensink also found that a large proportion of the Alaska sea otter population was concentrated around some of the western Aleutians; Amchitka was estimated to have the largest sea otter population of any island in the chain.

In 1955, Karl W. Kenyon, FWS Wildlife Biologist, began a study of sea otter biology that continued, in the field and in the laboratory, for over a decade. Much of his research was done in the western Aleutians and especially at Amchitka. The work culminated in the publication of a monograph covering essentially every aspect of the biology and natural history of the sea otter (Kenyon, 1969). It was largely through Kenyon's observations and experiments that the problem of captive mortality was solved, making it feasible to successfully transport animals to suitable habitats hundreds of miles from the point of capture. Sea otters have since been reintroduced into areas from which they had earlier been eliminated (Abegglen, Chap. 20, this volume).

Other facets of natural history were not neglected during the FWS sea otter investigations. Krog (1953) reported his observations on birds of Amchitka made during his visit to the island in 1952 in connection with sea otter parasitology studies. He includes a section on food habits of the Bald Eagle, noting evidence of eagle predation on young otters. Kenyon (1961) published an annotated list of the birds of Amchitka Island, a list totaling 69 species. He gives a brief history of the FWS program to exterminate foxes and rats and speculates on the probable adverse effects of these predators on avian populations.

The report by Kenyon and Rice (1961) on the abundance and distribution of the Steller sea lion is based mainly on surveys made in 1959 and 1960. A large proportion of the total estimated population was in the western Aleutians; a total of 1750 animals was estimated for Amchitka. Kenyon (1965) also reported on the food habits of harbor seals at Amchitka.

Other investigations of various aspects of the Amchitka ecosystem have been made in recent years by FWS personnel. For the most part, the results of these studies are unpublished and are available only in FWS files.

INTERNATIONAL NORTH PACIFIC FISHERIES COMMISSION

After the Alaskan salmon fisheries study of 1903 (see the catalog of Alaskan fishes by Evermann and Goldsborough, 1907) and the Aleutian cruise of the *Albatross* in 1906 (Gilbert and Burke, 1912), there seems to have been a long period of relative inactivity in oceanographic and fisheries

research in the western Aleutian region by American investigators. Some information was accumulating on the oceanographic features and commercial fisheries potential of the area, but there was no attempt at organized exploration until the second half of the twentieth century. The state of knowledge of oceanography of the North Pacific and Bering Sea and the sources of information were reviewed by Fleming (1955) and Dodimead, Favorite, and Hirano (1963). These reviews were published as Bulletins 2 and 13, respectively, of the International North Pacific Fisheries Commission (INPFC).

The INPFC was established in 1953 by an International Convention entered into by Canada, Japan, and the United States. Since the inception of the Commission, it has been the chief coordinating agency and the principal source of support for oceanographic and fisheries research in the seas around the Aleutian chain. The main focus of INPFC research is on conservation of commercial fisheries resources (principally Pacific salmon) and on allocation of rights to these resources among the participating nations. However, much basic information on the marine biota and the oceanography of the region derives from INPFC activities. The scope of INPFC research in the oceans adjacent to the western Aleutians between 1955 and 1960 is shown in Manzer et al. (1965, Figs. A-1 to A-6). These figures plot the location of stations occupied by INPFC research vessels during each year of the 6-year period; Japanese or American vessels, or both, occupied stations in the western Aleutian Islands during at least part of every year of the period covered. Many stations were well offshore, reflecting the objectives of the cruises, but a number were located near the chain, particularly in the vicinity of major passes between the North Pacific Ocean and the Bering Sea. Results of INPFC research are presented in annual reports, a bulletin series, and in various technical journals and government publications (Canadian, Japanese, and American).

WILIMOVSKY

The first systematic effort to investigate the inshore fish fauna of the Aleutians was made by Wilimovsky and his associates as part of a regional ichthyological inventory. Wilimovsky (1964) reports: "The purpose of this phase of the study was to conduct an ichthyological reconnaissance of the heretofore little known inshore fauna of the Aleutian Islands. Field investigations extended over a three-year period and were supplemented by limited material presently extant in museum collections." It is significant that, in his brief review of

previous investigations, Wilimovsky refers exclusively to early collections, e.g., those reported by Bean, Turner, and Evermann and Goldsborough. He also notes that "Recent Russian general works . . . make no major increase in the knowledge of the area."

Wilimovsky lists 135 inshore fish species* from the Aleutian Chain. Of these, about two-thirds of the species were found to occur in the western islands and about one-third were found at Amchitka. He emphasizes the reconnaissance nature of the study, the implication being that a more intensive investigation would probably add to the inventory. More important, he points out that "The really diverse and rich fauna is to be found in the immediate sub-tidal zone. We hardly know the composition of this stratum at a single location and future efforts should be concentrated on this belt." Simenstad et al. (Chap. 19, this volume) show that the recent Amchitka investigations did, in fact, provide an opportunity for more intensive sampling of the fish fauna in deeper waters around the island.

Wilimovsky concludes, on the basis of his extensive collections, that "After eliminating species occurring throughout the North Pacific basin, the remaining Aleutian Island fish fauna shows a closer relation to the American continent than to boreal Asia." He also notes the high proportion of Cottidae in the fauna and the existence of several endemic cottid forms that "... range from the mid-Aleutians westward to the Komandorskis."

RUSSIAN INVESTIGATIONS

Russian scientists made important contributions to knowledge of marine biology and oceanography of the North Pacific basin during the period covered by this chapter. Studies made in the vicinity of the Commander Islands are of special interest to us since these islands are, geographically, an extension of the Aleutian chain (O'Clair, Chap. 18, this volume). This review does not do justice to the Russian contributions, however, since I have had access to only a few translated references; much of the important Russian-language source material has not been translated into English.

The *Atlas of the Invertebrates of the Far Eastern Seas of the USSR* (Pavlovskii, 1955) cites 80 Russian works, published between 1878 and 1953, as "... the main general references on the Far Eastern seas." Many more specialized reports

dealing with particular classes of invertebrates are cited in other sections of the Atlas. Few of these numerous references are available in English translation.

Finally, mention should be made of the Bering Sea Comprehensive Scientific-Commercial Expedition of the Soviet institutes TINRO* and VNIRO†, more commonly referred to simply as the Bering Sea Expedition, which initiated a series of oceanographic cruises in the Bering Sea and North Pacific Ocean in 1958. The purposes of the expedition are best set forth by Moiseev (1964):

Thus, the vast potential of the northeastern Pacific Ocean remained untapped, especially with respect to benthic and demersal items At the same time, catches of most stocks of flatfish, herring, crabs, and other items had reached their limit due to natural population fluctuations (sic), and fishing even had to be reduced because of the depressed condition of these staple stocks of Far Eastern fishery.

The Bering Sea Expedition therefore had the problem of discovering new fertile fishing grounds for the Far Eastern trawling fleets, highly experienced and well equipped for this type of fishing.

This statement, by one of the architects of the expedition, suggests that the principal objective was the discovery of commercially exploitable fishery stocks, especially those susceptible to harvesting by Soviet trawlers. Studies of oceanography and marine biology were focused mainly on features that had a direct bearing on the fishery. Most cruises worked primarily in the eastern Bering Sea or in the Alaska Gulf, although one 1960 cruise followed the Commander Islands-Aleutian Islands arc, making several crossings between the Bering Sea and the Pacific Ocean (one such crossing was apparently through Amchitka Pass). Indirectly, the expedition has added significantly to knowledge on a regional level of such features as oceanic circulation; physical, chemical, and biological properties of the major water masses; and the biology of commercially important marine fauna.

SUMMARY

From the foregoing it is clear that Amchitka was by no means a *terra incognita* at the start of the investigations reported in this volume. Every aspect of the natural history of the western Aleutians had already been studied to some extent. Amchitka, one of the larger and more accessible islands in that part of the chain, had not been slighted by previous investigators. There were still

*Mostly intertidal, as indicated by the discussion of collection techniques.

*Pacific Ocean Scientific Research Institute of Fishery and Oceanography, U.S.S.R.

†All-Union State Research Institute of Marine Fisheries and Oceanography, U.S.S.R.

important gaps in the knowledge of Amchitka ecosystems when plans for the AEC-supported bioenvironmental program were being formulated in 1967, but the earlier work discussed in this chapter provided a valuable base for the studies reported in subsequent chapters.

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Geomorphology

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Amchitka Island is composed of six distinct geomorphic regions. The major elements of each region are strongly controlled by geologic structure and to a lesser degree by rock type. The eastern three regions are characterized by pond-dotted uplands of low elevation. These are surrounded by areas of one or more elevated marine terraces. Structurally controlled drainageways cut the terraces and extend into the upland. A thick blanket of organic-rich soils forms a nearly complete mantle over the regions. Across region IV farther west, elevations rise to the mountain and plateau regions. The crest upland becomes increasingly dissected, and the blanket of organic-rich soils shows increasing signs

of erosion. Much of the Pacific seacoast of regions III and IV is flanked by a broad nearly continuous intertidal platform.

Region V is one of considerable relief contrast and prominently displays the effects of past glaciation, higher sea-level stands, and current mass-wasting processes. Region VI is dominated by a wind-stripped crest plateau above broad amphitheater-shaped valleys that have many features in common with the cirque-form valleys of region V. The blanket of organic-rich soils is well developed only at low elevations near the coasts.

Amchitka Island is composed of volcanic breccias and conglomerates with locally important pillow lavas, intrusions, and volcanically derived sedimentary rocks (Carr and Quinlivan, 1969). Tectonic forces have resulted in numerous north-east-trending cross-island faults and fracture zones. Other structural trends are locally important. Marine, glacial, periglacial, fluvial, and eolian processes have interacted to produce the island's diverse geomorphology.

Powers, Coats, and Nelson (1960) recognized three main physiographic divisions of Amchitka Island, a high and low plateau segment separated by a mountainous segment. Within this general frame of reference, I (Everett, 1971) divided the island into six physiographic regions (Fig. 1), each displaying distinct geomorphic elements, processes, and rates of development. These regions correspond closely to the island's major rock types and structural elements. In the following sections each region will be considered separately beginning with region I, which is at the east end of the island.

GEOMORPHIC REGIONS

Region I

Region I extends east from the east boundary fault of the South Bight graben (Fig. 1). Much of the south coast and the coast surrounding the eastern end of the region is of low relief. Elevations

grade from a wave-planed rock shelf very close to sea level to a nearly level and poorly drained platform at about 16 m (52 ft) [15 to 18 m (50 to 60 ft)]. This platform comprises much of East Cape but is narrow and intermittent along the north coast of the region. A possible marine terrace occurs at a still lower level on the south side of East Cape at an elevation close to 8 m (26 ft). The 16-m (52-ft) platform supports a thin cover of organic soils over bedrock and/or rounded cobbles. Few ponds are present, and the surface is littered with logs and other debris that attest to frequent inundation by tsunamis. Inland the terrain rises by way of a well-defined little-dissected sea cliff to a second somewhat basin-shaped platform with an elevation of about 30 m (100 ft). The platform contains numerous shallow bedrock- and cobble-floored ponds. The organic-soil veneer is thicker than that on the lower platform but is generally less than 20 cm (8 in.) in depth. It rests on rounded cobbles and boulders of quartz-diorite or sometimes on bedrock.

A prominent sea cliff terminates the second platform and surrounds a shallow basin-shaped upland ranging in elevation between 55 and 70 m (180 and 230 ft) which contains a large number of shallow cobble- and bedrock-floored ponds. These ponds and those of the lower platform do not have a well-integrated drainage to the sea. Many appear as isolated individuals, and others have a poorly defined centripetal drainage pattern. Still other

Fig. 1—Index map of Amchitka Island and place-names referred to in this chapter and boundaries of physiographic regions.

ponds appear to be connected by shallow wet depressions to ponds on the periphery of the platforms which, in turn, drain down the old sea cliffs by way of poorly developed stream channels. Those draining over the highest sea cliff have eroded it more extensively than those draining over the next lower one.

In areas along the north coast of region I where a 15- to 18-m (50- to 60-ft) platform is developed, cliffs composed of jointed quartz-diorite rise 15 m (50 ft) from the sea. At some points the platform is littered with angular quartz-diorite boulders up to 0.6 m (2 ft) in diameter for a distance of up to 30 m (100 ft) inland from the sea cliff (Fig. 2). The boulders are accompanied by turf blocks 1 m (3 ft) or more in diameter which may be found 50 m (164 ft) inland. Most of these blocks of rock and turf were probably derived by seismic sea waves from near the top of the numerous joint-controlled square-shaped embayments in the sea cliffs. The driftwood litter on the platform at East Cape attests to the frequency of such events. The little-weathered appearance of both the turf and the diorite blocks suggests a relatively recent event, perhaps as recent as the 1957 tsunami that swept into Constantine Harbor. In a seismically active region like the Aleutian

Islands, such events are geologically quite frequent; however, their geomorphic expression is probably very localized.

South Bight Graben

The South Bight graben crosses Amchitka Island northwest to southeast and separates geomorphic regions I and II. The graben is filled with unconsolidated quaternary sediments (Gard, Chap. 2, this volume). Its surface descends from a near vertical cliff of 30 to 47 m (100 to 155 ft) elevation at the head of South Bight to about 16 m (52 ft) elevation at the head of North Bight. The area lacks significant geomorphic expression except for an area of low partially stabilized sand dunes at South Bight. The boundary faults of the graben are marked on the east by a northeast-southwest alignment of ponds and on the west by a series of generally aligned ponds, all with straight fault-controlled west shorelines.

Region II

Region II extends westward from the South Bight graben to a similar graben that forms the axis between Constantine Harbor and Makarius Bay. The coastline generally is irregular although not

Fig. 2—Quartz-diorite boulders thrown inland onto 12-m (40-ft) marine terrace, Bering Sea coast, physiographic region I.

deeply embayed. The north coast along much of its length is bordered by a narrow, sometimes interrupted, platform at 12 to 15 m (40 to 50 ft) elevation. This platform is generally absent from the south coast where cliffs rise nearly vertically 15 to 30 m (50 to 100 ft) from shallow, submerged fringing reefs. Sea stacks are numerous on both coasts, especially along the south coast, as are rocks and the truncated bases of former sea stacks, which are exposed or awash at low tide.

The relatively featureless central portion of region II ranges between 55 and 70 m (180 and 230 ft) elevation and probably represents, as Powers et al. (1960) suggest, the undissected remnants of a wave-cut platform. On this platform the numerous ponds or groups of ponds are isolated from each other or at best are connected by very poorly integrated drainages.

Along a line slightly north of the old military road, a well-defined northeast-trending drainage pattern heads toward the upland. As the coast is approached, absolute elevations between the drainage lines and the interfluvies range to 30 m (100 ft) or more. Many of the streams emerge onto discontinuous, although well-developed, remnants

of the 12- to 15-m (40- to 50-ft) terrace through deep V-shaped valleys. The side slopes of these valleys reach 50° or more and like the rest of the region are covered with a thick and generally stable mantle of peat or organic-rich mineral soil.

South of the central "upland" of region II, the ponds, and to a lesser degree the drainage, become strongly oriented to the east-northeast or east. This orientation, like that of the north coast, reflects structural control by faulting and probably also by jointing. These structurally controlled ponds are, as a group, probably the deepest on the island with depths between 1.5 and 5 m (5 and 16 ft). Because the 12- to 15-m (40- to 50-ft) marine terrace is absent along the southern coast, streams enter the sea there directly through narrow, deep valleys.

Constantine Harbor Graben

The Constantine Harbor–Makarius Bay axis (Fig. 1) marks the position of a second cross-island graben, which separates geomorphic regions II and III. The Constantine Harbor graben is morphologically more distinct than the one at South Bight in that its bounding faults are marked by prominent

rounded scarps that are as much as 30 m (100 ft) in height. The graben floor is at about 23 m (75 ft) elevation near the middle of the island. The graben contains several tens of meters of unconsolidated glaciomarine deposits. The presence of former glacial ice within the graben is known from recently exposed bedrock striations and what appear to be till deposits at Kirilof Point. The latter may record two separate glaciations (Gard, Chap. 2, this volume).

Region III

Geomorphic region III begins at the western margin of the Constantine Harbor graben and extends to the northwest to the vicinity of Banjo Point (Fig. 1). The region is similar to region II in that it consists of a nearly level to slightly basin-shaped central upland with an average elevation of approximately 40 m (130 ft). Below the blanket of organic soils are rounded gravels, probably of marine origin, which suggests that the upland may be an ancient marine platform (Powers et al., 1960).

Marine Features. The Bering Sea coast of region III is characterized by smooth sweeping shore segments. Landward from a narrow (few tens of meters) discontinuous intertidal platform is a wave-worked boulder beach (Fig. 3). Most of the boulders are derived from the volcanic conglomerate that forms the local bedrock. The active beach merges gradually with an intermittently active storm beach composed of boulders, sand, and tree trunks. The more elevated portions of this storm beach are densely overgrown by *Elymus arenarius* and *Senecio* sp. along with some succulents. Storm-wave activity on this portion of the beach is probably very infrequent and possibly confined to tsunami-generated waves. Behind the storm beach low vegetation-covered sea cliffs rise to approximately 7 m (23 ft). Inland, in some areas such as Crown Reefer Point, is a broad pond-dotted platform with a general surface elevation of 23 m (75 ft). Actively eroding headlands and sea stacks are few except east of Bridge Creek (Fig. 1).

The Pacific coast is less straight than the Bering coast and is characterized by embayments between 0.5 and 1 km (0.3 and 0.6 mile) wide which extend inland 300 m (985 ft) or more beyond the flanking and actively eroding headlands. The larger (broader) embayments usually have wide cobble and boulder beaches. Streams entering such coves commonly must flow in a channel through a rampart of storm-stranded logs and sand. Such areas appear to be well above most present severe storm waves. They support a rank growth of *Elymus arenarius* and *Senecio* sp., and many are

sites of Aleut middens (McCartney, Chap. 5, this volume). Other embayments are narrow and commonly bulb shaped with narrow cobble or boulder accumulations at their heads. Narrow headlands separate the embayments, and much of the coast is flanked by a broad intertidal platform or strandflat (Fig. 4).

The origin and significance of strandflats have been debated since the mid-nineteenth century. In keeping with views recorded by Fairbridge (1968), strandflats have probably been formed by a combination of subaerial and biochemical weathering of (in the case of Amchitka) the weakly cemented Chitka Formation. Most of the weathering products have probably been removed to deeper water beyond the platform. Fairbridge (1968) considers biochemical weathering, as well as minor amounts of mechanical weathering, to be restricted to a very limited area near shore. If this is true, then the extensive platforms of the Pacific coast represent a substantial period of time in which both isostatic and eustatic changes of sea level were minor or absent. Milliman and Emery (1968) believe this time to be on the order of 4000 years, and Black (1974) argues for a period of approximately 8000 years for similar features on Umnak Island. The major cutting according to Black (1975) was between 8250 and 3000 years B. P.

Observations of the Amchitka platforms suggest that the nearly complete cover of *Fucus* sp. and related forms (Lebednik and Palmisano, Chap. 17, this volume) as well as encrusting algae and sponges effectively protect the majority of the platform from mechanical weathering at all times of the year and that the platform itself serves to check the impact of waves reaching the shore as they break on its seaward edge. If for some reason the cover of organisms is destroyed and the biologically weathered(?) surface is periodically exposed to the agents of mechanical weathering, a reduction in surface height can be expected. Such a circumstance occurred when a portion of an intertidal platform was permanently exposed to subaerial conditions as a result of the Cannikin test. In the 2 years following that event, the near-shore portion of the platform has been reduced by between 1 and 2 cm. This rapid rate of erosion will probably slow down as less and less biologically weathered rock remains and as the surface is sealed by what appears to be a form of case hardening.

By whatever mechanisms, cliff recession and the production of intertidal platforms have created numerous small sea stacks from the more-resistant portions of the bedrock (Fig. 5). They seldom occur far from shore and are geologically very transitory features of the coast.

Fig. 3—Sea cliffs removed from active marine erosion. Note imbricated cobble beach. Bering Sea coast, physiographic region III.

Fig. 4—Intertidal platform. The surface is covered with *Fucus* sp. Note old weathered rockfall at the base of the headland. Pacific coast, physiographic region III.

Fig. 5—Sea stack rising from a segment of intertidal platform. Pacific coast, physiographic region III.

Although the extensive areas of broad intertidal platforms in regions III and IV argue for what may be a rather protracted period of tectonic and isostatic stability, the elevated and fossil shorelines, terraces, and sea cliffs indicate periods of past instability.

It has been suggested that the broad upland of region III originated from marine planation (Powers et al., 1960). A prominent terrace backed by a sea cliff [base at approximately 22 m (72 ft)] occurs from a point east of Rifle Range Point to Duck Cove (Fig. 1). Less extensive terrace remnants at this elevation occur in other areas of region III, notably Crown Reefer Point, and terraces at similar elevations have been described in regions I and II.

Powers et al. (1960) reported possible marine-terrace remnants between 3 to 5 m (9 to 16 ft) elevation. Gard (Chap. 2, this volume) questions whether features at this level represent high sea-level stands and suggests that they may be related to the present storm beaches, such as that shown in Fig. 3.

Ponds. The upland has a large number of ponds. Those of the central portion are similar to, although appreciably larger and more numerous than, those of the uplands of regions to the east. The ponds may occur either as isolated individuals or as isolated interconnected groups and show no

clearly identifiable relationship with underlying bedrock structures. Commonly the connection between ponds is through a shallow neck of water. Numerous small turf islands characterize many of the larger ponds [4 ha (10 acres) or more], and water levels in adjacent ponds and pools may differ by 0.5 m (1.5 ft) or more.

The waters of most of these ponds drain through tortuous ill-defined and often subterranean channels, eventually reaching a major surface drain leading to the sea.

The bottoms of the larger individual ponds or members of pond groups have characteristics that range widely and unpredictably. Some have 30 cm (12 in.) of flocc (low-density organic and detrital suspension) over gravel; others have organic silts or gravels, and still others have relatively clean gravel floors. The bottoms of a majority of the ponds are gently shelving to depths that probably average less than 1.5 m (5 ft).

The shorelines of the larger ponds are highly complex, and the surrounding turf is sometimes undercut as a result of wave action. One to three elevated or abandoned shorelines are a common feature.

Interspersed between the larger ponds are a great number of smaller ones that are usually less than half an acre in area, many of which show no drainage connections with each other or with the

regional drainage. The smaller shallower ones, 30 to 50 cm (12 to 20 in.) deep, have flat bottoms that are generally composed of peat or fine sediments covered with some floc. The pond bottom meets the surrounding turf barrier or "shore" at nearly a right angle. This is attributed to ice push during the frequent winter freezes. Wave action is probably ineffective in eroding the margins of these small ponds and pools.

The origin of the ponds in this geomorphic region is undoubtedly complex. Some isolated individuals may be related to random bedrock irregularities. For the majority, however, an evolutionary succession from flat-bottomed pools to large coalesced ponds is suggested.

Shacklette (1961) interpreted the sedge-meadow pools of Latouche Island, Alaska, as having been formed as a result of the damming of minor surface drainage by growth of one or more sedge tussocks accompanied by mosses. The initial small pool thus formed is thought to have increased in size as vegetation growth increased the height of the dam and as ice formed during the fall freeze-up extended and pushed the dam back.

A similar mechanism could account for most of the ponds on the peat-covered uplands and terraces of Amchitka. Here the ill-defined, sluggish, and apparently often aimless drainage could easily be blocked by vegetation growth. The numerous small flat-floored ponds and pools of these areas may reflect the initial stages of pond formation. As the pools expand owing to an increase in the marginal dam height, it is natural that they would coalesce, producing still larger though not necessarily deeper ponds with complex shore outlines, islands, and narrow interpond connections. The large upland ponds, especially of regions II and III, appear to be relatively stable features at least over short time intervals. Comparison of 1948 and 1968 air photography indicates few morphologic changes, although there are numerous examples of pond drainage through breaching of a peat dam or in one case collapse of a portion of the pond bottom into an underground drainage channel. Pond elimination by encroachment of vegetation has not been documented.

Drainage. In region III the major drainages have cut well into the central pond-dotted upland just discussed. The streams throughout their courses occupy narrow, sinuous, slightly incised paths. In their lower courses a number of the larger streams have cut 30 m (100 ft) or more below broad interfluvies that are sloping projections of the central "upland." Many streams are graded to present sea level; others descend to the beach over a prominent bedrock knickpoint that is perhaps

related to a greater local resistance to weathering of the bedrock or to a higher stand of sea level at about 6 m (20 ft) elevation.

Several drainages, e.g., Bridge Creek, have broad flat-floored channels confined by banks 8 m (25 ft) or more high (see Chap. 9, Fig. 3, this volume). These valleys have not been cut by their present streams, which flow in narrow deep channels more than 1 m (3 ft) deep cut in peaty materials. Perhaps, as Powers et al. (1960) suggest, they owe their cross-profile to glacial action; however, in the case of Bridge Creek Valley, faulting probably accounts for this form. Regardless of the time and mode of their formation, some of the broad valleys have been recently aggraded. A large alluvial fan occurs near the mouth of a broad valley northwest of Makarius Bay. The fan was probably produced during a period of intensive erosion in the watershed, possibly after recession of the last ice.

Glacial Features. Evidence for the existence of glacial ice on Amchitka Island has already been cited for the graben structures, especially the Constantine Harbor graben. In region III a prominent scarp related to the Rifle Range Fault crosses the island in a northeast-southwest direction from Galion Pit to the Bering Sea coast. Quaternary marine gravels or glaciomarine deposits lie against the scarp to the northwest (Morris, 1971). These gravels are probably equivalent to those in the South Bight and Constantine Harbor grabens (Morris, 1971; Gard, Chap. 2, this volume).

Additional evidence for the presence of glacial ice on region III takes the form of shallow flutes in the recently exposed bedrock on a smoothly contoured prominence between Crown Reefer and Banjo Points. The form of the flutes, as well as the *roche moutonnée* shape of the prominence, indicates a local ice motion from southwest to northeast, probably emanating from an ice center in the middle of region III.

Region IV

The transition between geomorphic regions III and IV is abrupt. Upland elevations increase at the east end of region IV from about 55 m to 70 m (180 to 230 ft) and gradually rise to nearly 200 m (655 ft) in the west near Chitka Point. The amount of undissected pond-dotted upland decreases to the west until near Chitka Point only isolated remnants of the upland remain at elevations between 165 and 200 m (540 and 655 ft).

The divide crest is displaced far toward the northeast (Bering Sea side) of the island. This probably reflects the presence of the more easily

weathered rocks of the Banjo Point Formation which occupy a belt about 0.8 km (0.5 mile) wide adjacent to the Pacific coast of region IV.

The drainage, still oriented northeast-southwest, is better integrated in region IV than in region III. Channelized drainage below the peat mantle is much less extensive. Many streams, especially those entering the Pacific Ocean, head in broad amphitheater-like basins separated from one another by narrow disconnected projections of the crestral upland. From a distance numerous linear elements can be seen paralleling the sides of the seaward-projecting interfluves. These may be manifestations of distinct lithologic units or structural trends in the bedrock.

Marine Features. Much of what has been written concerning the coastlines of region III applies to region IV. The Bering Sea coast of region IV maintains a smoothly contoured outline. Headlands embracing narrow embayments [less than 200 m (655 ft)] are prominent features, especially from Banjo Point west to Sand Beach Cove. The portion of the beach exposed to wave action is composed mostly of cobbles and small boulders. Locally, as at Sand Beach Cove, sand is the major component of the beach material. Throughout much of the length of the Bering Sea coast of region IV, cliffs rise precipitously 55 to 65 m (180 to 215 ft) above the narrow beach.

The large arcuate embayments that characterize the Pacific coast of region III are found in region IV, but these display a serrated profile, i.e., many small (50 by 50 m; 164 by 164 ft) embayments are superimposed on the larger coastal embayments. Vegetation-mantled sea cliffs average 16 m (52 ft) in height. The fringing intertidal platform remains well developed to the western boundary of the region.

An interrupted but well-defined sea cliff at 40 m (130 ft) base elevation parallels the Pacific coast of region IV. This feature is best developed from the eastern boundary of the region to a point just west of Mex Island (Fig. 1). The cliff and associated platform at an average elevation of 23 to 30 m (75 to 100 ft) are breached by the major drainages (Fig. 6). Flat to gently seaward-sloping interfluves at 40 m (130 ft) elevation extend from the cliff base. West of Mex Island and from 0.7 to 0.8 km (0.5 mile) inland from the coast are terrace remnants with surface elevations ranging between 68 to 78 m (225 to 255 ft). These surfaces together with the 40-m (130-ft) cliff base are probably related to terraces or platforms at similar elevations noted in regions I to IV.

Streams entering the Bering Sea have shorter courses, steeper gradients, and are generally less well integrated than those just described entering the Pacific. Marine features at higher elevations

Fig. 6—Eustatic marine terrace, 23 to 30 m (75 to 100 ft) above present sea level. Pacific coast, physiographic region III.

comparable to those of the Pacific coast are more difficult to recognize on this side of the island within region IV. However, a significant break in slope does commonly occur at elevations between 68 and 78 m (225 and 255 ft).

Mass Wasting. Accompanying the change in landform that occurs across region IV are changes in geomorphic process. Whereas the more easterly regions presented an aspect of geomorphic stability, region IV, with its increasing elevation westward, shows abundant evidence of slow mass movement on the slopes and the effects of wind deflation on the uplands. Contour-oriented turf-banked terraces commonly occur downslope from undeformed interfluvial crests. The processes of slope movement are enhanced by increased frequency of the freeze-thaw cycle at the higher elevations in the western part of region IV.

The more spectacular forms and features of mass wasting, landslides, and landslide-produced topography are not common on Amchitka Island. However, in region IV, southeast of Low Bluff on Chitka Point (Fig. 1), are large multiple-stepped slumps (see Chap. 2, Fig. 5, this volume) that involve deposits of the Chitka Point Formation. The largest slump has an area of about 1 km² (Gard, Chap. 2, this volume). Gard attributes the formation of the slumps to sea-level fluctuations during the Pleistocene. These fluctuations presumably altered hydrologic conditions within the mass or removed its stabilizing toe portion. Slump triggered by earthquake shock cannot be ruled out.

There is ample evidence that rockfall from present exposed sea cliffs that surround much of the island is common and accounts for most of the natural cliff recession. Especially in region IV, the products of these falls accumulate on the intertidal platform at the base of the headlands or cliffs exposed to wave erosion. Most falls are small, involving a few to several hundred cubic meters, and are quickly removed (a few decades or perhaps centuries) by a combination of subaerial weathering and wave erosion. Other falls, removed from constant wave attack, weather rapidly and are quickly colonized by plants to form stable landscape elements or are removed by storm waves.

Many of the near-vertical sea cliffs have a veneer or overhanging curtain of peat, parts of which become detached from time to time. Such turf falls are quickly removed by storm waves or simply by weathering of the organic matter. Most turf falls and rockfalls are probably induced by vibrations from pounding storm waves or by earthquakes.

The Cannikin underground test of 1971 induced extensive and large-volume rockfalls, espe-

cially from headlands, as well as turf slides and falls from areas between the headlands. Because of the combination of faults and deeply weathered and fractured bedrock, the cliff failures resulting from this event were greatest on the Bering Sea coast of region IV, amounting to an estimated 30,000 m³ (39,000 yard³) of material. Wave action and subaerial weathering and erosion in the years following the test have modified the form of these falls, removing parts of some and producing a fine textured rooting medium on others.

The Pacific coast of region IV was less heavily distributed by the Cannikin test. It is estimated that some 5000 m³ (6500 yard³) of rock and turf were shaken down.

The lower yield Milrow test of 1969 accounted for much less rockfall and turf fall. The coastal area most effected was in region III. One rockfall at Square Bay accounted for 45% of the estimated total of 6900 m³ (9000 yard³). It is probably safe to say that the nuclear testing, especially the Cannikin test, accomplished in an instant the cliff erosion that would have taken centuries or longer by geologic processes.

Windblown Sand Deposits. Mention has already been made of an area of small semiactive dunes at South Bight. Other more-extensive deposits of windblown sand are developed on the cliffs fronting the Bering Sea in region IV. These deposits consist of an asymmetrical mound of medium and fine sand at the top of the sea cliff. The lee slope tapers inland. In addition to their form, such areas are easily recognized by the dense rank stand of *Elymus* which they support. The sea-cliff face below the dunes commonly has a veneer of sand up to 60 cm (24 in.) thick which also supports a dense stand of grass. Such cliff faces are most common on the coast between Banjo Point and a point just to the west of Sand Beach Cove.

Black (1974) considers such sand veneers (climbing dunes) on Umnak Island as having been initiated about 8000 years ago, or about the time of strandflat construction. Judson (1946) suggested that dune deposits on Adak Island may have formed when a greater sand source was exposed, possibly during a glacial low sea level.

With very few exceptions, such as at Sand Beach Cove, Amchitka lacks extensive areas of subaerially exposed sands. It is probable that the primary development of the cliff-top dunes and sand veneer of the sea cliffs occurred during periods of lowered sea level, perhaps as long ago as 8000 years.

The sand veneer of the sea cliffs is unstable (slope angle of 40° or more). In some areas active

step-like sand slips mark the cliff face and expose the sands. Ground shock from the Cannikin test caused extensive sliding of the temporarily stabilized sand veneer along some portions of the coast in region IV. At present sand from these exposures as well as some from the beach is moved by strong on-shore winds up along the cliff face and over the top of the cliff where it is deposited. This phenomenon probably also occurs aperiodically as a result of earthquakes as the very poorly developed soils and buried thin organic horizons in the dunes suggest.

Region V

The fifth geomorphic region begins near Chitka Point where crest elevations rise to between 185 and 360 m (610 and 1180 ft) and extends to the vicinity of Midden Cove (Fig. 1). A general accordance of remnant summit surfaces at elevations between 322 to 328 m (1055 to 1075 ft) might reflect a once extensive marine terrace, or more probably the surfaces are the products of cryoplanation operating on the lithologically homogeneous and dense Chitka Point Formation.

Marine Features. The change in coastline form between region IV and V is as marked as the elevation change. Both the Bering and Pacific coastlines are deeply indented. Midden Cove on the Bering coast and White House and Signal Coves on the Pacific coast are 1000 m (3300 ft) or more wide and extend inland 1000 to 1500 m (3300 to 4900 ft). Smaller coves from a few to 100 m (330 ft) in width also project inland for distances up to 100 m. Only in the large coves are there significant cobble and boulder beaches. Headlands are narrow, and all are undergoing active erosion.

Sea cliffs are composed mostly of bare rock and commonly rise very steeply to nearly vertically 60 to 200 m (200 to 655 ft) above the sea. Sea stacks are numerous along both coasts but especially along the Pacific coast. Several small but prominent islands occur close offshore. Windy Island, in the Pacific Ocean, approximately 400 by 300 m (1300 by 985 ft) in plan dimension, reaches an elevation of nearly 95 m (310 ft). In the Bering Sea, Vista Island in Burr House Cove and an unnamed island in the Chapel Cove area have elevations in the 30- to 46-m (100- to 150-ft) range. Other islands occur around the near shore of Amchitka, but, with the exception of Bat Island [28 m (92 ft)] off the Bering Sea coast of region III, Mex Island [40 m (130 ft)] off the Pacific coast of region IV, and Bird Rock and nearby islets [23 to 33 m (75 to 110 ft)] off Bird Cape in region VI, nearly all have elevations less than 20 m (66 ft).

Perhaps the most prominent geomorphic elements of this most highly dissected region of the island are the four major north-facing cirque-form valleys. The valleys head in steep scree-covered slopes and are separated from one another by high-angle sharp-crested *arête* ridges (Fig. 7). A narrow ridge that supports many of the remnant summit surfaces runs west to east down the length of the region and divides the north-facing cirque-like valleys from broader and much less distinct amphitheater valleys that open south to the Pacific.

The smooth bowl form of a typical cirque basin is lacking in these north-facing valleys. Instead the valleys descend from the base of the headwall in three (sometimes four) distinct levels. The origin and significance of these levels are debatable. They may represent remnants of marine-erosion levels or reflect lithologic changes in the bedrock. The correspondence in elevation of at least two of the levels with those of other regions of the islands favors a marine origin.

The lowest level, which is at about 16 m (52 ft), is sporadic in occurrence and extends far into the cirque basin. In several areas apparently inactive debris cones occur at the mouths of both intermittently active and inactive drainages that exit on this level. Near the present coast, isolated remnants of a second terrace occur between 30 and 46 m (100 and 150 ft). This is partly within the elevation range of a marine terrace described by Gard in region I (Gard, Chap. 2, this volume). A third prominent break in slope occurs at approximately 76 m (250 ft). Like the second level it corresponds closely in elevation to a marine transgression described from region I (Gard, Chap. 2, this volume). Old and apparently inactive debris fans also terminate at this level.

The fourth distinct slope break and/or terrace occurs between about 165 and 195 m (540 and 640 ft) elevation. This level may be coextensive with similar summit levels in the adjacent geomorphic regions. Gard also recognizes a level close to these elevations and suggests that it originated by the process of cryoplanation (altiplanation) rather than marine erosion. An imbricated sedimentary sequence, including rounded to subrounded boulders and cobbles and laminated coarse clay-rich sands, which are apparently the hornblende "andesite" gravels described by Powers et al. (1960), occurs on upland positions between 140 and 165 m (460 and 540 ft) in region IV. If these deposits are marine (a fluvio-glacial origin cannot be dismissed), then the fourth level in the cirque-like valleys of region V may be the product of marine erosion.

Fig. 7—Crest of the island, elevation 325 m (1066 ft), and cirque headwalls. View to west, physiographic region V.

Glaciation. One of the most compelling pieces of evidence for glaciation in region V is the well-developed cirque forms, especially those facing the Bering Sea. However, no unquestioned glacial deposits were found in the cirque valleys. Because of the short distance between the cirque bowl and the sea, most of the material eroded by ice would now be below sea level. Powers et al. (1960) describe striations on bedrock exposures within the cirques which they attributed to glacial action. I was unable to find any striations that I would be willing to attribute to glacial action. The relative softness of the volcanic rocks and the intense weathering, both physical and chemical, contribute to accentuation of lineations, i.e., microfractures, as well as to the destruction of true glacial markings.

The occurrence of terrace remnants in these valleys suggests that they have not been occupied by ice with any significant erosive power, at least during the Wisconsin Stage and possibly the Illinoian as well. This assumes that the cirque terrace between 30 and 47 m (100 and 155 ft) is equivalent to that associated with marine deposits in South Bight dated by Gard (Chap. 2, this volume) at 127,000 years.

Large long-lasting snowbank accumulations do not now occur near the headwalls of the cirques. Neither is there an indication that snow accumu-

lates preferentially in these valleys as opposed to those facing the Pacific since at present there is no prevailing wind direction (Armstrong, Chap. 4, this volume). What appears to be a small protalus rampart occurs in a valley facing Midden Cove (Fig. 1). The origin of this feature together with the scree-covered headwalls and the sharper more-distinct form of the north-facing cirques, may lie in an increased frequency of freeze-thaw. The headwalls of the north-facing cirques do not receive direct solar heating as do those of the south-facing valleys.

The south-facing amphitheater-like valleys appear much less cirque-like than those just described. They are broader, more subdued in form than the north-facing valleys and are topographically more complex. Three major step-like levels analogous to the upper three in the north-facing valleys occur in these valleys.

The general north-trending linearity that characterized the *arêtes* and valleys facing the Bering Sea is complicated in the south-facing valleys by a series of west-trending fault traces. This cross-cutting structure imparts a rectangular plan to the individual topographic elements in these valleys.

Mass Wasting. Active mass wasting (and deflation) occurs throughout region V, especially above 76 m (250 ft) elevation. The forms produced by the mass-wasting processes include turf-banked

terraces (Fig. 8), which are especially well developed in the area of hydrothermally altered rocks (Carr and Quinlivan, 1969), in the area from Chitka Point to the west side of Chitka Cove (Fig. 1) and on either side of the island's crestal ridge. In these and similar forms, weathered debris is moved downslope over the frontal risers of the terraces, which are oriented obliquely to the contour, as well as along the treads. Turf-banked terraces are commonly associated with solifluction lobes. Debris stripes occur in region V, but they are neither well developed nor extensive. They form by the coalescence of the obliquely oriented terraces.

Large, often multiple (stair-like) solifluction lobes move down many of the hillslopes (Fig. 9). Many of these lobes appear to be moving away from deflated crest positions. It is common to find near the center of these deflated crests a rock pinnacle (tor) or less commonly a core of bedrock surrounded by organic soil (Fig. 10). It is clear that the tors are disintegrating under a combination of frost action and chemical weathering and that the debris produced by these processes is undergoing comminution in transit away from the crest. The lobate front that surrounds many of the wind-stripped crests and is farthest away from the tor is actively overriding organic soils and vegetation.

Some tors support a thick cap of organic soil; where no bedrock is visible, it appears that deflation and solifluction have left only an isolated remnant of a once extensive cover of organic soil. These circumstances suggest that the blanket bog so extensively developed at present over the eastern regions of the island may have accumulated and extended farther west and to higher elevations in the not too distant past. In view of the tectonic stability of the island, the destruction of organic mat might imply a slight climatic change.

An alternate and perhaps better interpretation would be that the eastern portion of region V and the western portion of region IV record in their altitudinal transition a shifting balance between the processes of organic-matter accumulation and destruction. This receives further consideration in Chap. 9, in which the island's soils are discussed.

Sorted forms of patterned ground are not abundant in the region. Sorted circles, however, such as those in Fig. 11, occur commonly in the moist basins of former or intermittent ponds. The forms shown in this figure are at about 155 m (510 ft) elevation and appear to be active.

The valley slopes, especially the headwalls and arête-like projections of the crest ridge, are steep, 30° or more. Many are stable, particularly at lower elevations where extensive areas have thick organic soils developed on the scree or blocky talus. In

view of the radiocarbon dates obtained for organic soils in other regions of the island (Everett, Chap. 9, this volume), it is likely that much of the now-stable talus accumulated under a periglacial climate following retreat of the Pleistocene ice. These "stable" slopes are commonly interrupted or overrun by tongues of active talus projecting from the upper block-covered portion of the slope or from deflated uplands. The frequency of occurrence of these active talus interruptions increases with increasing elevation.

What appears to be a stabilized felsenmeer has developed in a few areas where the crest divide broadens out so that a relatively level expanse occurs (cryoplanation remnants). The individual blocks are heavily encrusted with lichens and are surrounded by a matrix of highly decomposed organic soil.

Region VI

The separation between physiographic regions V and VI is drawn along the east side of the Midden Cove valley system (Fig. 1) and across Infantry Road between mileposts 32 and 33 to the Pacific coast at Signal Cove. Across this line and to the west in region VI, crest elevations decrease from approximately 350 m (1150 ft) (region V) to about 250 m (820 ft) in a distance of 0.8 km (0.5 mile). The upland becomes a plateau with a surface that broadens and eventually decreases somewhat in elevation to the northwest. This broadening or flattening is probably due in part to a change in lithology of the Chitka Point Formation along a line trending south from Burr House Cove (Gard, Chap. 2, this volume).

Marine Features. The present coastline of region VI differs from that of region V in that the embayments are smaller, usually less than 0.5 km (0.3 mile) wide, and penetrate inland less than 0.3 km (0.2 mile) beyond the narrow headlands. Much of the coast, even within the embayments, is rocky, very steep, and terminates in deep water; thus the development of intertidal platforms is much restricted. However, small sea stacks associated with the headlands are numerous.

The Aleut Point—Bird Cape area at the western end of the island is an exception to the above. Here a marine-eroded platform is surrounded by a discontinuous sand and cobble beach that in some cases extends for 50 m (164 ft) inland. Behind the beach are near-vertical vegetation-covered cliffs 16 to 30 m (52 to 100 ft) high. Inland from the sea cliff, platform elevations gradually rise to 76 m (250 ft) at the base of an ancient sea cliff. The platform is most broad at Aleut Point where elevations are generally between 16 and 30 m (52

Fig. 8—Contour-oriented turf-banked terraces. Note the numerous spillover tongues. Physiographic region V.

Fig. 9—Large multiple-solifluction sheet with contour-oriented turf-banked terraces. Physiographic region V.

Fig. 10—Tor developed on crest ridge. Note the distribution and general decrease in size of rock fragments away from core. Some similar features retain a cap of organic soil. Physiographic region V.

Fig. 11—Large active sorted circles developed in the basin of an intermittent shallow pond. Physiographic region V.

and 100 ft). Many ponds occur on this portion of the platform, producing an aspect similar to the pond-dotted areas of regions III and IV. In general, ponds are more numerous in region VI than in region V. In the area south of the crest plateau, between Signal Cove and a point 1.5 km (0.9 mile) northwest of Rim Point (Fig. 1), the elongation of many ponds and their general northwest alignment, together with a well-developed rectangular drainage, suggest structural control. However, the principal drainages of region VI trend northeast or southwest and reflect the major structural control of the cross-island faults. These drainages head in broad amphitheater-shaped basins similar to those of region V.

In these basins are remnants of three rather distinct topographic levels. The best developed of these terminates at the 76-m (250-ft) contour, which appears to be coextensive with the base of the fossil sea cliffs at Aleut Point and Bird Cape. In an area northwest of Rim Point, a pair of ancient debris cones terminate on this level (Fig. 12). Similar cones associated with the 76-m (250-ft) terrace were described in region V.

A terrace level at 155 m (510 ft) has been identified in region VI. It is the site of numerous ponds, especially in the eastern portion of the region near Rim Point.

A mesa-like feature, Square Bluff (Fig. 1), has upland elevations that range between 225 and 250 m (740 and 820 ft). The surface is mostly composed of lag gravel in which Powers et al. (1960) noted very-well-rounded pebbles and cobbles. These investigators could not conclude whether the rounded materials were derived from the bedrock conglomerate or were products of marine planation. A similar feature designated C. P. Bluff lies to the south of Square Bluff but is lower in elevation, 180 m (590 ft).

Glacial Features. The glacial record is somewhat better preserved in region VI than elsewhere on the island. Powers et al. (1960) described polished and striated surfaces in the region. Although I did not find them to be as abundant as Powers et al. indicated, I did observe them at several localities. Good striations were recorded on a divide near mile 38 of the Infantry Road at an elevation of 155 m (510 ft).

Several rounded erratic blocks (Fig. 13) were noted at about 137-m (450-ft) elevation near the crest and on the seaward flanks of rounded knolls overlooking Signal Cove. The blocks are erratic, not in the sense that they are of a bedrock type foreign to the area but rather in form and position. The blocks may have originated upvalley either

Fig. 12—Ancient and/or possibly intermittently active debris fans spilling onto a 76-m (250-ft) eustatic marine terrace. Physiographic region VI.

Fig. 13—Glacial erratic at 137-m (450-ft) elevation. Possible source is approximately 1 km (0.6 mile) away. Shovel is 1 m (3 ft) in length. Physiographic region VI.

Fig. 14—Inactive stone stripes leading from felsenmeer-covered upland. Physiographic region VI.

from the steep "headwall" leading to the upland plateau or from equally steep southeast-facing valley walls approximately 1 km (0.6 mile) northwest. Viewed from the upland, the amphitheater valley as a whole has the sculptured or smoothed appearance that results from ice motion.

Mass Wasting. In the eastern two-thirds of region VI, the upland plateau surface and its spur-like extensions have elevations that range between 225 and 250 m (740 and 820 ft). Of this surface 40 to 60% is composed of lag gravel, with fragments mostly 2.5 to 8 cm (1 to 3 in.) in diameter with a few ranging up to 30 cm (12 in.). It is probable that at one time Square Bluff was coextensive with this surface.

What appear to be partially stabilized or in some cases eroded sand dunes (coppice dunes) are common to the plateau surface together with low [<50 cm (20 in.)] deflation scarps. Turf-banked terraces with broad treads [up to 3 m (10 ft) in width] occur on sloping areas of the plateau surface and are oriented obliquely to the contour. The terraces of the steeper slopes commonly coalesce to form stripes. Similar but less extensive terraces occur on the rounded hills and prominences at lower elevations. Well-developed "fossil" stone stripes (Fig. 14) occur on a hillslope near mile 39 at an elevation of about 116 m (380 ft). A soil similar to that of the inactive felsenmeer in region V is developed on this surface.

A single sporadically active landslide is developed on the relict sea cliff flanking the 76-m (250-ft) terrace below C. P. Bluff. A comparison of aerial photographs indicated that the slide originated between 1948 and 1967. It developed at a slight concave break in slope and is probably the result of oversaturation of the organic soils and consequent movement over bedrock. At frequent intervals the slide continues to extend upslope by sapping its headwall.

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Soils

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Three organic soils, or Histosols, are recognized on Amchitka Island which represent the suborders of Fibrists, Hemists, and Folists. The Fibrists and Folists have very restricted distribution, occupying, respectively, some of the topographically most depressed and wettest and topographically highest although not driest areas on the island. Hemists are one of the principal soils of the island. They occur as a blanket over much of the poorly drained central portions of the eastern half of the island as well as over marine terraces and other topographically low areas. Three mineral soils belonging to two soil orders are recognized. Two belong to the order Inceptisols. In terms of area, the most extensive of the Inceptisols belong to the great group of Cryaquepts. These soils are most commonly developed below 100 m (300 ft) and occupy sloping positions; they are at or near saturation for most of the year. Andic Cryaquepts occur toposequentially above the Hemists, with

which they may form an association. Above the Andic Cryaquepts in the topographic moisture gradient is a hummock phase of this soil. These soils are most commonly mapped as associations. At the dry end of the toposequence are the Cryandepts. These soils are most abundant above 100 m (300 ft), especially in the mountainous and/or topographically high western half of the island, where they are commonly associated with deflation pavements and mass-movement forms. Cryopsamments, which belong to the order Entisols, occur on sandy areas (dunes). They are areally restricted but are important especially along the Bering Sea coast of the central third of the island.

The soils of the island began to develop perhaps contemporaneously with or at least soon after recession of the island's Wisconsin ice cap, approximately 10,500 years B. P.

The soils of the Aleutian Islands have received only slight attention. The earliest descriptions are those of Ulrich (1946) from Adak Island. The early soil survey of Alaska (Kellogg and Nygard, 1951) refers to the soils of much of the Aleutian Islands, including Amchitka, as tundra (soils) without permafrost. Most recent investigations on Kodiak Island by Rieger et al. (1960) refer to some of the organic-rich soils as "ando-like." These soils are now classified as Cryandepts* (S. Rieger, personal communication) and are genetically similar to the soils derived from volcanic materials in Japan and many other volcanic islands.

The soils of Amchitka, and probably most of the other western Aleutian Islands, either are organic or contain large amounts of organic matter and volcanically derived materials. They have counterparts in other cool maritime environments, such as Iceland (Johannesson, 1960) and Scotland (FitzPatrick, 1964), as well as on other Aleutian Islands and parts of Japan. The organic soils of Amchitka have been described in detail by Everett (1968, 1971a, 1971b). The taxonomic position of the Amchitka soils is now considerably changed from that given by Everett (1971a).

*Soils nomenclature used in this report follows that of the U. S. Department of Agriculture Soil Taxonomy (Soil Survey Staff, in press).

CLIMATIC AND BIOTIC FACTORS

Both the climate and the vegetation of the island have been thoroughly discussed elsewhere in this volume. A few of the more salient aspects will be considered, however, to provide a background for a discussion of soils, which are so largely a product of these factors.

The temperature and moisture regime of Amchitka Island can be characterized as cool and moist with a relatively narrow seasonal amplitude in values (Armstrong, Chap. 4, this volume). The mean annual temperature range is 9.4°C. During the foggy summer the diurnal temperature may range only a few degrees (near 7°C) for many consecutive days. The mean daily range is 3.9°C or less for all months. Precipitation measurements from 1943 through 1948 indicate a yearly total of 620 mm. Measurements for 1968 through 1971 are significantly higher, averaging 978 mm/year (range, 670 to 1158). Although apparently any month may record the maximum, there is a well-defined fall and winter peak. These factors combine with a low evapotranspiration rate to provide optimum conditions for the growth of mosses, sedges, and some members of the Ericaceae and grasses. These plants together with prolific growths of foliose and fruticose lichens, especially at the lower end of the toposequence, form a thick carpet or blanket

covering even the steepest slopes. The organic residues that accumulate under these conditions produce the highly organic soils of the island. The high water-holding capacity of the blanket of living vegetation and the underlying peat maintain both the peat and underlying mineral substrate at or very near saturation the year round.

GEOLOGIC FACTORS

With few exceptions the volcanically derived bedrock of Amchitka is highly susceptible to chemical and physical breakdown. Weathering may extend a meter or more below the bedrock surface, especially where the products of breakdown are protected by an organic soil (Fig. 1). The intensely weathered volcanic breccias and conglomerates often take on the characteristics of glacial till. Some such deposits may, in fact, be glacial till, but very few can be so designated with certainty.

In terms of the present-day soils of the island, the characteristics of the weathered bedrock (mineral-soil substrate) influence only the shal-

Fig. 1—Section showing physical and chemical disintegration of bedrock beneath an organic soil.

lower organic soils and, of course, the development of mineral soils.

THE TOPOSEQUENCE

The peat and mineral soils produced in this cool maritime environment are arranged on the landscape along a topographic moisture gradient (toposequence) (Fig. 2). Topographically low areas near the base of the toposequence and broad

Fig. 2—Idealized toposequence showing the relationship among the principal soils.

poorly drained interfluvies common on the eastern half of the island where water tables are at or close to the surface throughout the year are the sites of organic soils.

Higher in the toposequence the soils generally lack a water table, although most are at or near saturation throughout the year.

NOMENCLATURE

The nomenclature used in the description and discussion of the mineral soils follows that of the U. S. Department of Agriculture's 1951 Soil Survey Manual and its 1962 supplement (Soil Survey Staff, 1951, 1962). Nomenclature pertaining to the organic soils and the classifying criteria for all soils follows the U. S. Department of Agriculture Soil Taxonomy (Soil Survey Staff, in press).

ORGANIC SOILS

Much of the lowland terrain of Amchitka Island is covered with a spongy carpet of lichens, sedges, and moss. The high water-retaining capacity of this vegetation together with the island's cool moist climate favors the accumulation of organic matter and the formation of organic soils. All organic soils belong to the order Histosols. Most Histosols are saturated with water and are more than half organic matter by volume. Depending on the clay content of their mineral fraction, Histosols

contain 12 or 18% (20% in the case of unsaturated Histosols) organic carbon by weight.

Three suborders of Histosols have been identified on Amchitka: Fibrists (soil "a1"), Hemists (soil "a2"), and Folists (soil "h").

Fibrists ("a1" Soils)

Fibrists are a suborder of Histosols composed largely of plant remains so little decomposed that they are not destroyed by rubbing and the botanic origin can be readily determined. Fibrists normally have low bulk densities, high water-holding capacities, and, in the absence of eolian or volcanic ash additions, low ash contents.

On Amchitka "a1" soils have a restricted areal extent and occupy the lowest position in the toposequence (Fig. 2). They may occur in old lake beds or mantling broad valley floors (Fig. 3). In most instances the midsummer water table stands within 30 cm (12 in.) of the surface. During late winter and spring or during abnormally wet periods, the water table may be at or slightly above the surface. They commonly support a dense, rather pure stand of *Carex* sp. growing in a thick mat of moss. Beneath this layer of living vegetation are one or more thin layers or horizons of moderately to highly decomposed very dark-brown (10 YR 4/2)* to black (10 YR 2/1) organic matter in a hemic or sapric decomposition state. Most of the profile to 1 m (3 ft) or more consists of a succession of horizons of little-decomposed reddish-brown (7.5 YR 2/2) to very dark reddish-brown (7.5 YR 3/2) coarse and medium fibrous organic material (fibric state of decomposition) (Fig. 4).

The island's soils have a Cryic temperature regime, i.e., they have a mean annual temperature above 0°C but below 8°C. Because of the maritime climate of the island, they seldom freeze to a depth of 5 cm (2 in.). In recognition of the above criteria, the prefix Cryo is used to differentiate at the great group level.

Disseminated mineral materials, including discrete layers of volcanic ash or sand, are rare in these soils, thus probably all the Fibrists may be classified within the typic subgroup as represented by the following profile:

Classification:	Typic Cryofibrist.
Vegetation:	<i>Carex</i> sp., <i>Empetrum nigrum</i> , and minor amounts of <i>Cladonia</i> spp.
Topography:	Valley bottom; slope angle, 0°.
Microrelief:	Flat or having small hum- mocks 3 to 5 cm high.

*All colors are Munsell designations and refer to moist or wet soils.

Drainage:

Poor to very poor; periodic standing water; water table 48 cm on Sept. 4, 1967.

Depth, cm	Horizon	
3-0		Mat of living mosses.
0-5	Oa1	Black (5 YR 2/1) sapric peat; 25 to 30% fiber; slightly sticky; boundary abrupt and smooth.
5-10	Oe1	Dark reddish-brown (5 YR 3/2) hemic peat, fine fibrous; boundary abrupt and smooth.
10-18	Oi1	Dark-brown (7.5 YR 3/2) fibric peat, medium and coarse fibrous; boundary clear.
18-51	Oi2	Dark-brown (7.5 YR 3/2) fibric peat, color appears slightly darker than above; boundary abrupt and smooth, water table at 47.5 cm.
51-55	Oi1	Very dark-brown (7.5 YR 2/2) fibric peat, coarse fibrous; boundary abrupt and smooth.
55-57	Oe2	Dark-brown (10 YR 3/2) hemic peat and loamy sand; slightly sticky; boundary abrupt and smooth. (Probably an ash layer.)
57-67	Oi4	Dark-brown (7.5 YR 3/2) fibric peat, medium fibrous; boundary gradual and smooth.
67-85	Oi5	Dark-brown (7.5 YR 3/2) fibric peat, coarse fibrous; some mineral material; boundary abrupt.
85-108	Oi6	Very dark-brown (7.5 YR 2/2) fibric peat, coarse to very coarse fibrous; profile terminated.

Hemists ("a2" Soils)

Hemists are organic soils whose constituent plant materials have been decomposed enough so that the fibers are largely destroyed by rubbing and the botanic origin of two-thirds of the materials cannot be identified. They have intermediate bulk densities and soil moisture.

On Amchitka these soils occur on gentle slopes (3 to 10°) near the bottom of the idealized toposequence where they are commonly adjacent to or transitional to the better drained mineral soils (Fig. 5). The "a2" soils also occupy large areas of relatively poorly drained uplands or raised marine terraces, especially in physiographic regions I to III (see Fig. 1, Chap. 8, this volume, and maps I to IV in the pocket at the back of this volume).

Fig. 3—Flat-floored aggraded stream valley with dense stand of sedges. Site is typical for “a1” soils.

Fig. 4—Soil “a1” displayed against typical vegetation. (A) Thin sapric horizon and (B) fibric organic matter.

Vegetation is composed of sedges, lichens (primarily *Cladonia pacifica*), and grasses: the “breakaway” tundra and sedge-lichen meadow of Amundsen (1972 and Chap. 10, this volume). The abundant easily decomposed lichens impart a gelatinous and slippery character to the soil horizon immediately below the living vegetation.

In general, the soil profile is composed of a succession of organic horizons, both hemic and fibric, extending down to about 1 m (3 ft) (Fig. 6) with the hemic texture dominating. The mineral-organic contact has been observed to consist of a concentration of rounded or subrounded cobbles and boulders, frequently rotted, in a finer grained matrix. The upper horizons, both hemic and fibric, tend to be somewhat darker than those lower down in the profile.

One of the most characteristic elements of this soil is the two, occasionally three, thin mineral layers. The upper layer occurs at an average depth of 15 cm (6 in.). The lower two layers are found between 23 and 38 cm (9 and 15 in.). Thin-section and grain-mount analyses have established these layers as volcanic ash. These will be considered in more detail later.

The temperature regime of the “a2” soils is similar to that of the “a1” soils. Therefore they are classified as Cryohemists at the great group level. The presence of layers of volcanic ash requires the term Fluvaquentic at the subgroup level of classification.

Fig. 5—Toposequence distribution of some of the principal soils of Amchitka. (A) soil "a2," (B) soil "b," (C) soil "bh," and (D) soil "c" and partially deflated surface.

The following profile is illustrative of "a2" soils:

Classification:	Fluvaquentic Cryohemist.				
Vegetation:	<i>Antitrichia curtipendula</i> and <i>Empetrum nigrum</i> . Reindeer lichen (<i>Cladonia</i> spp.) and scattered <i>Carex</i> spp.; surface has a general brown or rust-brown appearance.		25-28	C1	than 5 to 10 cm; roots many; boundary abrupt and smooth.
Topography:	Rounded hill—approach slope; slope, 5°; S-SE exposure.		28-47	Oa2	Light olive-brown (2.5 Y 5/4), loamy sand; fine roots common; massive; boundary abrupt and smooth.
Microrelief:	Slightly uneven, low broad hummocks, no pattern, 15 to 30 cm.				Very dark grayish-brown (10 YR 3/2), very dark grayish-brown squeezed (10 YR 3/2) sapric peat, a few sand grains or nodules; rubs down with moderate ease; considerable coarse fibrous material; roots common; boundary gradual.
Drainage:	Very poorly drained.				
Depth, cm	Horizon				
8-0		Mat of living vegetation.			
0-3	Oa1	Dark yellowish-brown to very dark-brown (10 YR 4/4 to 10 YR 2/2) gelatinous layer under vegetation carpet; roots common; boundary abrupt and smooth.	47-55	Oe3	Very dark grayish-brown (10 YR 3/2), dark-brown squeezed (7.5 YR 3/2) hemic peat; boundary abrupt and smooth.
			55-68	Oe4	Very dark grayish-brown (10 YR 3/2) hemic peat; boundary abrupt and smooth.
3-10	Oe1	Dark yellowish-brown (10 YR 3/4), dark-brown squeezed (7.5 YR 3/2) hemic peat; roots many; boundary gradual.	68-75	IIC2	Dark grayish-brown (2.5 Y 4/2) very fine sand and silt with some mixed fibrous peaty material; massive; boundary abrupt and smooth.
10-25	Oe2	Dark-brown to brown (7.5 YR 4/2), dark-yellowish-brown squeezed			

75-105	Oi1	Dark-brown (10 YR 3/3), very dark grayish-brown squeezed (10 YR 3/2) fibric peat; boundary clear.
105-120	Oi2	Dark-brown (10 YR 3/3) to very dark grayish-brown (10 YR 3/2) fibric peat; boundary clear and smooth.
120-135	Oi3	Dark-brown (7.5 YR 3/2) fibric peat; boundary clear and smooth.
135-158	Oi4	Very dark grayish-brown (10 YR 3/2) fibric peat; boundary abrupt and smooth.
158-165	IIC3	Yellowish-brown (10 YR 5/4) very fine sandy loam, few organic fragments; boundary abrupt and smooth.
165-175	Oi5	Very dark grayish-brown (10 YR 3/2) fibric peat; boundary not observed.

Fig. 6 - Profile of soil "a2." Note the large lichen component in present vegetation. (A) Hemic peat, (B) ash layer, (C) hemic peat, (D) ash layer, and (E) fibric peat.

No geographical or topographical variations were noted for "a1" soils. In "a2" soils, however, two such variants were noted. Typically "a2" soils have 2 to 8 cm (1 to 3 in.) of living vegetation over the soil surface. However, in certain areas near the coasts and more commonly on hillslopes, soils having an "a2" profile have developed over them as much as 30 cm (12 in.) of spongy living moss, ferns, and *Carex* spp. These soils commonly have a higher field moisture status than is typical of "a2" soils. Possibly they represent the position of a seep. Such soils are most frequently encountered in physiographic regions I to III. When they comprise a sufficient area to appear on the soils maps (maps I to IV in the pocket at the back of this volume), they are designated by the letter "t," indicating the thick mat phase.

The second variant occurs most commonly in physiographic regions III to VI. Again the profile is that of an "a2" soil, but the amount of disseminated mineral matter (sand grains) increases substantially. In these regions "a2" soils are commonly closely associated with lag gravel surfaces, and the sand in their profiles is windblown from these surfaces. Toward the coast in these regions (away from extensive lag surfaces) the modal profile is developed.

Folists ("h" Soils)

These more or less freely drained Histosols are comprised primarily of O horizons resting on rock or on fragmental materials consisting of gravel, stones, or boulders. The organic materials completely or partially fill the interstices. The "h" soils are restricted to physiographic regions V and VI where they are developed on felsenmeer-covered uplands that are presently stable (Fig. 7).

Profiles are characterized in the upper parts by relatively large amounts of coarse fragmental (rock) material in a matrix of brittle somewhat blocky or platy structured sapric organic material. With depth the amount of organic material decreases. Void space increases to about 30-cm (8-in.) depth until it may amount to 50% of the profile volume. Below 30 cm (8 in.) sandy or sandy-gravelly loam completely fills in around the fragmental material. In areas of the profile with considerable void space, the rocks commonly have small patchy encrustations of what appear to be salts but which do not react to HCl. Because unfractured bedrock occurs at depths greater than 1 m (3 ft), the Folists belong to the Typic subgroup.

Classification:

Vegetation:

Typic Cryofolist.

Empetrum nigrum, *Thamnia vermicularis*, *Lupinus nootkatensis* and *Salix* spp.

Fig. 7—Road cut in physiographic region VI showing soil "h" developed in shattered bedrock below a stabilized felsenmeer. Elevation is approximately 250 m (820 ft).

Topography:	Felsenmeer-covered upland, approximately 9-m down-slope from bedrock outcrop. Slope angle, 5°.			platy structure; rock fragments 80% in the 8- to 13-cm range, void space below 18 cm is less than 10%; skeleton surfaces clear, roots common and concentrated in voids; boundary clear and wavy.	
Microrelief:	Lag boulders and cobbles. Relief to 15 cm.				
Drainage:	Well drained.				
Depth, cm	Horizon				
2.5-0		Mat of vegetation between boulders.	25-34	B21	Dark yellowish-brown (10 YR 3/4) very fine sandy loam; organic matter high; massive, crushes to moderate, medium angular blocky to weakly platy structure; rock fragments 15 to 20%; voids absent; roots common; boundary clear and wavy.
0-10	Oa1	Dark-brown (7.5 YR 3/2) sapric material; contains some mineral material; massive, somewhat brittle,* breaks to weak, moderate angular blocky structure; skeleton 50 to 60% in range 5 to 13 cm; larger fragments have salt encrustations; mineral material fills in around skeleton; roots many; boundary clear and wavy.	34-46	B22	Dark-brown (10 YR 3/3) sandy loam; massive, breaks to moderate, medium, coarse subangular blocky structure, also may be somewhat friable and granular; very coarse sand and granules 30% of horizon; boundary clear and smooth.
10-25	Oa2	Dark-brown (7.5 YR 3/2) sapric material; massive, breaks to weak, medium, coarse angular blocky and	46-48	B3	Dark yellowish-brown (10 YR 4/4) fine to me-

*Characterizes crushing resistance.

*Characterizes crushing resistance.

dium sandy loam; little organic matter; massive, breaks to moderate, medium, subangular blocky and granular structure; rock fragments 75% in the 2- to 8-cm range; no voids; roots absent.

MINERAL SOILS

Four distinctive kinds of mineral soil are recognized on Amchitka Island. Three of these, designated "b," "bh," and "c," belong to the order Inceptisols, i.e., predominantly fine-textured soils having weakly developed horizons showing some form of physical and chemical alteration. Both soils "b" and "bh," because of their high organic content, were formerly considered to belong within the order Histosols (Everett, 1971a). On Amchitka the Inceptisols occupy the more-elevated positions in the toposequence (Fig. 2) and occur in all physiographic regions of the island. They are the dominant soils westward from about the middle of physiographic region IV (see maps I to IV in the pocket at the back of this volume).

The fourth mineral soil, designated "e," is probably best placed within the order Entisols. Soil "e" exhibits little or no evidence of the development of pedogenic horizons. This soil occupies a narrow discontinuous strip along the coastal bluffs, primarily those facing the Bering Sea.

Inceptisols

Aquepts. This suborder of Inceptisols contains the two most widely distributed soil types on Amchitka Island, types "b" and "bh." These soils occupy sloping terrain and are wet. Although the soils are at or very near saturation at all times, they commonly lack a water table, i.e., a surface of zero pore water pressure. Exceptions occur from time to time after heavy rains, especially in soil "b" where it is developed low in the toposequence.

Both "b" and "bh" soils have conspicuous organic-rich horizons in their upper part. However, in both cases either the aggregate thickness of the horizons or their organic carbon content is insufficient to permit the inclusion of these soils within the order Histosols as it is currently defined.

"b" Soils. Soils of "b" type are widely distributed over the island, increasing in extent from east to west. They occur topographically higher than "a2" soils on slopes ranging to 30° or more (Figs. 2 and 5).

The morphology of soils included within the "b" group ranges widely. In positions transitional to the toposequentially higher (and better drained)

"bh" soils, the horizon succession is dominated by highly decomposed sapric materials to depths of 50 cm (20 in.) or more. When the soil is transitional to "a2" soils, the profile depth may reach 1.75 m (5 ft) and contain less decomposed histic material. In fact, in such positions Histosols may occur.

The modal profiles of midslope positions are developed under crowberry-sedge grass vegetation (Amundsen, 1972), and moderately decomposed organic materials dominate the upper horizons.

The thin mineral (ash) layers similar to those of the "a2" soils normally occur in "b" soils. In addition to these layers, discontinuous zones of soft iron hydroxide or iron hydroxide-organic materials are precipitated at textural discontinuities—often at the interface between the highly organic horizons and the predominantly mineral substrate. If the iron compounds have been subjected to oxidation, they assume a reddish color and the deposits may harden and become impermeable. The deposits are then referred to as ironstone and usually mark the position of a former water table. In many profiles abandoned root channels are coated with iron oxides, and the sapric materials may be mottled with oxidized iron.

In "b" soils, especially those better drained and toposequentially above the modal, a columnar fracture pattern commonly develops in the sapric organic materials. These fractures are somewhat open and coated with organic-iron hydroxide.

The contact between the organic-rich horizons and the mineral horizons is generally sharp. The mineral materials can be separated on the basis of texture and color into two or more horizons. They are usually reddish or dark reddish-brown (oxidized) loams or sandy or gravelly loams. Most contain some organic matter (see chemical analysis, Appendix A, Table A.1*). The upper mineral horizon is commonly indurated with iron and silica, indicating deposition from downward-percolating and/or laterally moving waters.

The term Andic is used at the subgroup level of classification to recognize the occurrence of pyroclastic material within the upper 75 cm (30 in.) of the profile.

The following "b" profile taken in physiographic region II is representative of the modal or central concept of this soil.

Classification:	Andic Cryaquept.†
Vegetation:	<i>Empetrum nigrum</i> ; grasses, <i>Carex</i> spp., and <i>Gladonia</i> spp. Coverage, 100%.

*Chemical and physical analyses for "b" soil are from profiles similar to that which follows but are not from that profile.

†Chemical data in Table A.2 are from a soil similar to the one described here.

Topography:		Southeast-facing slope; length, 10 m; slope angle, 14°.			strong, coarse angular blocky structure; yellowish-red (5 YR 5/8) flecks and root coatings; fine roots common; boundary abrupt and smooth.
Microrelief:		Slight hummocks of vegetation 5 to 30 cm.			
Drainage:		Poorly drained (midslope position).	28-33	IIC2	Dark yellowish-brown (10 YR 4/4) silt loam (volcanic ash); massive; breaks to strong, coarse subangular blocky to very weakly platy structure; numerous red (2.5 YR 4/8) root casts; dark-red (2.5 YR 3/6) ped coatings; fine and medium roots many; boundary abrupt and smooth.
Depth, cm	Horizon				
5-0		Mat of living vegetation.			
0-5	O1	Very dark-brown (10 YR 2/2) hemic peat; wet; gelatinous; coarse and fine roots many; boundary clear and smooth.			
5-12	All	Very dark-brown (10 YR 2/2) organic silt loam; massive; wet; structureless when wet; moderate, medium to coarse subangular blocky structure when dry; fine roots many; boundary clear and smooth.	33-37	A16	Black (10 YR 2/1) organic silt loam; moderately brittle; crushes to strong, medium to coarse subangular blocky and granular structure; numerous red (2.5 YR 4/6) root casts; fine roots common; boundary clear and smooth.
12-14	A12	Black (10 YR 2/1) organic silt loam; massive; very moist, very slightly brittle; crushes to moderate strong granular structure; fine roots many; boundary abrupt and smooth.	37-45	A17	Very dark grayish-brown (10 YR 3/2) organic silt loam; massive; very slightly platy; breaks to strong, coarse angular and subangular blocky structure; slightly vesicular; tendency to vertical fracture; 20% fine and very fine sand; numerous red (2.5 YR 4/6) root casts to several millimeters thick; reddish-brown (5 YR 4/4) mottles; fine and medium roots common; boundary abrupt and smooth.
14-16	C1	Dark-brown (10 YR 3/3) fine sandy loam (volcanic ash); considerable organic matter; massive; crushes to weak, coarse to medium angular blocky to subangular blocky structure; fine roots common; boundary clear and smooth.			
16-20	A13	Black (10 YR 2/1) organic silt loam; moist; massive; slightly brittle crushes to weak, medium to coarse subangular blocky structure; fine roots common, many show oxidation coatings; boundary clear and smooth.	45-55	A18	Black (7.5 YR N2/) organic silt loam; massive to weakly friable; slightly vesicular; crushes to strong, coarse and very coarse angular and subangular blocky structure; strong vertical fracture; fracture walls strongly vesicular; mottling much reduced; roots common; oxidation casts few; boundary abrupt and wavy.
20-25	A14	Very dark-brown (7.5 YR 2/2) organic silt loam; massive; breaks to moderate, medium subangular blocky structure; fine and medium roots many; oxidation coatings as in above horizon; boundary abrupt and smooth.	55-65	B2	Dark grayish-brown to brown (10 YR 4/2-4/3) loam; massive; slightly vesicular; tendency to vertical fracture, weakly platy; crushes to very strong, coarse angular blocky structure; infill around boulders up to 1 m in diameter; slight mottling around boulders; roots common; boundary clear to wavy.
25-27	IIC2	Very dark grayish-brown (10 YR 3/2) fine sandy loam (volcanic ash); massive; breaks to weak, medium angular blocky structure; fine roots common; boundary abrupt and broken.			
27-28	A15	Black (7.5 YR N2/) organic silt loam; massive, moderately brittle; crushes to			

Brown (10 YR 4/3) fine gravelly loam; massive; weakly indurated; crushes to strong, coarse angular blocky structure; large boulders common; cobbles, 30%; small granules rounded and highly weathered.

"bh" Soils. In the toposequence position above soil "b" in physiographic regions I to IV, a microtopographic pattern of hummocks and depressions occurs. On sloping positions these features become drawn out into a ribbed pattern by the processes of solifluction. The soils of such areas, designated "bh" soils, are morphologically similar to soil "b," and, like soil "b," are classified as Andic Cryaquepts. In some areas, notably in physiographic region III, "bh" soils developed under hummocks may occur in association with "a2" soils.

The unusual surface morphology as well as certain physical characteristics (see Tables 1 to 3) of these areally significant soils is recognized in their classification by the addition of a phase term (hummock). An analogous separation is also made in the vegetation by the designation Crowberry Stripe (Amundsen, 1972).

Where possible the "bh" or Andic Cryaquept Hummock Phase soils have been mapped separately (maps I to IV in the pocket at the back of this volume), otherwise they form an undifferentiated complex with "b" soils (Fig. 8).

Profiles from all regions of the island show "bh" soils to be somewhat shallower than "b" soils. Highly decomposed organic [sapric] materials dominate the organic component of the soil.

Most of the organic-rich horizons offer some resistance to crushing. Under pressure the massive material breaks to moderately or strongly developed angular or subangular blocky or occasionally platy structural units. This characteristic is well developed in "bh" soils and may reflect an amorphous component in the mineral fraction and/or the addition of organometallic precipitates. A natural, larger scale, blocky or rhomb-shape structure is commonly developed in "bh" soils (Fig. 9) and is like similar forms developed in "b" soils. The block faces nearly always have ferromanganese coatings. Also, small, moderately hard iron or manganese nodules are common in some horizons. Volcanic ash layers, so prominent in "a2" and "b" soils, are rare and fragmentary in "bh" soils.

Fig. 8.—Valley head in physiographic region V in which soil "b" (A) and soil "bh" (B) can be mapped separately and where they are mapped as an association (C).

Fig. 9.—Prominent cracks developed in a “bh” soil. In three dimensions a rhomb-shaped unit is defined by the cracks. (A) Sapric organic material and (B) mineral material.

The following profile is a modal representative of the “bh” soil from physiographic region I.

Classification:	Andic Cryaquept Hummock Phase.*
Vegetation:	<i>Empetrum nigrum</i> , <i>Cladonia pacifica</i> , <i>Cladonia</i> spp., <i>Calamagrostis nutkaensis</i> , and <i>Rhacomitrium lanuginosum</i> . Coverage, 100%.
Topography:	Interfluvial area, physiographic region I.

*Chemical and physical data in Table A.2 are from a soil similar to the one described here.

Microrelief:	Alternating depressions and hummocks, 30 to 50 cm; scattered, large, conical vegetation mounds.
Drainage:	Moderately well drained.
Remarks:	Profile through a hummock.
Depth, cm	Horizon
5-0	All
0-5	Mat of living vegetation. Dark reddish-brown (5 YR 2/2) organic silt loam; high percentage of coarse stems and roots of <i>Empetrum nigrum</i> ; boundary clear and wavy.

5--12	A12	Very dark-brown (10 YR 2/2) organic silt loam; massive to somewhat friable; very weak, coarse granular structure; fine roots common; boundary clear and wavy.
12--15	A13	Black (5 YR 2/1) organic silt loam; massive; moist; breaks to very weak, coarse, angular blocky structure; fine roots common; boundary abrupt and wavy.
15--18	A14	Dark reddish-brown (5 YR 2/2) organic fine sandy loam (ash); roots common; boundary clear and interrupted.
18--30	A15	Very dark grayish-brown (10 YR 3/2) organic silt loam; massive; slightly brittle; breaks to weak, coarse angular blocky structure; contains 5% $\pm$ mineral and scattered gravel fragments 1 to 3 cm; roots common; boundary clear and wavy to interrupted.
30--38	A16	Black (5 YR 2/1) organic silt loam; massive; moderately brittle; crushes to strong, medium to coarse angular and subangular blocky structure; occasional rounded gravel fragments 1 to 3 cm; roots few; boundary clear and wavy.
38--55	A17	Black (7.5 YR N2/) organic silt loam; wet; massive; iron hydroxide concretions abundant; rounded fine and medium gravel fragments, 70%; top of gravel clean, sides and bottom have organo-mineral accumulation; rock fragments, 80%+; roots few; boundary clear and abrupt to wavy.
55--65	B21	Dark-brown (7.5 YR 3/2) silt loam; massive to slightly indurated; breaks to strong, coarse, angular blocky structure; skeleton as above 2 to 8 cm in size; mineral soil acts as matrix; roots occasional; boundary abrupt, irregular.
65--73	B22	Very dark grayish-brown to dark-brown (10 YR 3/2-3/3) gravelly silt; rock fragments, 70%; wet; oozing water, darker colors appear to be organic coatings.

The underlying mineral materials are usually of gravelly or sandy loam texture and contain a high

proportion of ferromineral near the organic boundary which give way in depth to high concentrations of ferric iron.

Andepts

The suborder of Andepts contains the more or less freely drained Inceptisols having a low bulk density and containing a significant amorphous component or having a mineral fraction composed mostly of pyroclastic materials.

Beginning with region IV and continuing westward at elevations generally above 100 m (300 ft), the Andepts in "b" and "bh" soil landscape positions have strong morphologic resemblance to the modal concepts of these soils. However, they are better drained and contain a much higher mineral component. The mineral materials are believed to be derived mostly from adjacent deflation pavements. Many of these soils display weak thixotropic characteristics related to their montmorillonite and amorphous clay content. Both "b" and "bh" soils are classified as Dystric Cryandepts. Those soils with hummocky or ridged surface morphology bear the phase designation "Hummock." Away from mineral-soil sources and at lower elevations the Cryaquepts again dominate the appropriate landscapes.

The following profiles from physiographic region IV serve to characterize the Dystric Cryandep and the Dystric Cryandep Hummock Phase.

Classification:		Dystric Cryandep.
Vegetation:		<i>Carex</i> spp., grasses, <i>Empetrum nigrum</i> , mosses, scattered <i>Chrysanthemum arcticum</i> , and <i>Pedicularis chamissonis</i> .
Topography:		Northeast-facing slope just off upland surface. Slope angle, 15°.
Microrelief:		Uniform and even.
Drainage:		Well drained.
Depth, cm	Horizon	
5-0		Mat of living vegetation.
0-5	A1	Very dark-brown (10 YR 2/2) organic loam; uncrushed fiber, 20%, crushed, 5%; approximately 10% granules; horizon somewhat loose and friable; fine roots common; boundary clear and smooth.
5-10	A12	Dark-brown (7.5 YR 3/2) organic loam; 20%+ mineral granules to several millimeters; moist; massive; crushes to weak, medium angular blocky structure; boundary clear and smooth.

10-23	A13	Dark-brown (10 YR 3/3) fine gravelly to organic coarse sandy loam; pebbles up to several millimeters; organic matter content, 10 to 15%; massive; brittle; crushes to weak, moderate angular blocky structure; occasionally weakly platy; fine roots common; boundary clear and smooth.	73-83	B22	Dark-brown (7.5 YR 4/4) granular sandy loam; very moist; vesicular, vesicles have fine silt coatings; horizon massive; moderately indurated, moderately platy; breaks to very strong, coarse to very coarse angular blocky structure; granule fragments are mostly decomposed, roots absent.
23-35	A31	Dark-brown (7.5 YR 3/2) fine granular silt loam; massive; moist; slightly brittle; crushes easily to strong, coarse, subangular blocky to weakly platy structure; reddish-yellow (7.5 YR 6/8) flecks of oxidized iron around roots, structural units and weathered granular mineral material; slightly vesicular; fine roots common; boundary clear and smooth.	Classification:		Dystric Cryandept Hummock Phase.*
			Vegetation:		<i>Empetrum nigrum</i> , <i>Cladonia pacifica</i> , <i>Calamagrostis nuthaensis</i> , and <i>Salix</i> sp. Coverage, 100%.
			Topography:		Uniform east-facing slope (15°) downslope from deflation crest.
			Microrelief:		Hummocks to 38 cm with slight tendency to contour orientation.
			Drainage:		Well drained.
35-40	A32	Dark-brown (7.5 YR 3/2) loam; approximately 10% organic matter; moist; slightly brittle; crushes to strong, medium angular and subangular blocky structure; granules are absent; fine and medium roots are common; boundary abrupt and smooth.	Remarks:		Profile typical of segments IV to VI.
			Depth, cm	Horizon	
			5-0		Mat of living vegetation.
			0-5	All	Very dark-brown (10 YR 2/2) organic fine sandy loam; moist; massive to slightly friable; very weak fine granular structure; roots common; boundary clear and smooth.
40-45	A33	Dark-brown (10 YR 3/2-3/3) loam or silt loam; massive; crushes to strong to moderate, medium subangular blocky structure; mineral grains less than 1% completely weathered to reddish yellow (7.5 YR 7/6-6/8); roots few; boundary abrupt and smooth.	5-17	A12	Strong-brown (7.5 YR 3/4) organic fine sandy loam; massive to somewhat friable; weak, medium to fine granular structure; roots common; boundary clear and smooth.
			17-23	A13	Dark reddish-brown (5 YR 2/2) organic fine sandy loam; massive; slightly brittle; crushes to strong coarse angular blocky structure; roots common; boundary clear and smooth.
45-63	B11	Dark yellowish-brown (10 YR 3/4) loam; massive; slightly brittle; crushes to moderate, coarse, subangular blocky structure; vesicular; granule fragments less than 5%, most completely weathered; boundary clear and wavy.	23-29	A14	Dark-brown (7.5 YR 3/2) organic loam; massive to slightly friable; breaks to strong, medium granular structure; roots common; boundary clear and smooth.
63-73	B21	Dark reddish-brown (5 YR 3/4) granular loam; very moist; massive; slightly indurated; breaks to strong very coarse to coarse angular blocky structure; occasionally completely weathered cobbles surrounded by dark grayish-brown (10 YR 4/2) silt loam; boundary abrupt and smooth.	29-35	A15	Dark-brown (7.5 YR 3/2) organic loam; massive; slightly brittle; somewhat platy; breaks to moderate, medium to coarse angular and subangular blocky structure; ped interiors dark

*Soil not represented in chemical and mechanical analyses, Appendix A.

		yellowish brown (10 YR 3/4); roots common; boundary clear and wavy.
35-46	A16 (?)	Very dark grayish-brown to dark-brown (10 YR 3/2-3/3) organic silt loam; massive; moderately brittle; coarse platy; breaks to very strong, very coarse angular blocky structure; fine roots common; boundary clear and smooth.
46-63	A17 (?)	Black (10 YR 2/1) organic loam; massive; moderately brittle; breaks to very strong, coarse angular to subangular blocky or very weakly platy structure; rock fragments, 30%, increasing to 50%+ below; fragments clean; roots common; boundary clear and wavy.
63-73	B21	Dark-brown (10 YR 3/2) sandy loam; massive; moist; slightly brittle; breaks to strong medium to fine angular blocky structure; rock fragments, 15%, 2 to 3 cm (0.8 to 1 in.); roots few; boundary clear and smooth.
73-83	B22	Dark-brown (10 YR 3/3) gravelly loam; ped coatings very dark grayish brown (10 YR 3/2); massive; brittle; slightly platy; breaks to strong coarse to medium angular blocky structure; rock fragments, 60%; roots occasional; boundary clear and wavy.
83-88	B23	Dark-brown to dark yellowish-brown (10 YR 4/3-4/4) gravelly sandy loam; massive; moist; slightly brittle; breaks to strong medium angular blocky structure; rock fragments, 20%; occasional smears or patches of very dark grayish-brown (10 YR 3/2) loam; value and chroma increase to yellowish brown (10 YR 5/6) at 85 cm (34 in.).

A third soil type "c," also an Andept, occupies many upland crest positions and solifluction terraces. The "c" soils are intimately associated with deflation pavements where they may occur as soil "islands" on a lag gravel surface. The "c" soils also commonly occur marginal to lag gravel surfaces and are replaced at a slightly lower topographic position (Fig. 2) by Dystric Cryaquepts, especially the Dystric Cryaquept Hummock Phase. The "c" soils

are features primarily of physiographic regions IV to VI.

Ideally, "c" soils are developed under a nearly complete cover of Crowberry and grass, with *Lupinus nootkatensis* a common adjunct. Slopes are generally less than 2°; however, soils designated as "c" may occur on slopes as great as 30° associated with turf-banked terraces.

Typically the thickness of the A horizons ranges between 10 and 15 cm (4 and 6 in.), occasionally reaching 40 cm (16 in.). The increased drainage of these soils results in a high degree of oxidation, both of the organic materials and of the mineral soil. The addition of organic matter to the sandy-loam texture produces a loose strongly developed granular structure (the texture of a good commercial potting soil). Mineral-soil subhorizons range in texture from sandy loam to loamy sand and gravel, depending on the composition of the parent material. Occasionally a concentration of organic matter occurs above relatively unoxidized mineral soil, the possible significance of which will be discussed under a subsequent heading. Thixotropic characteristics are not well expressed in "c" soils, and they are placed in the Typic subgroup of Cryandepts.

The following profile is representative of the "c" soil.

Classification:		Typic Cryandept.
Vegetation:		<i>Empetrum nigrum</i> , <i>Lupinus nootkatensis</i> , scattered <i>Carex</i> spp., and <i>Thamnia vermicularis</i> .
Topography:		Near crest position, slope angle, 5°.
Microrelief:		Few scattered hummocks, 5 to 13 cm to smooth, sporadic eroded areas.
Drainage:		Well drained.
Depth, cm	Horizon	
0-5	A1	Very dark-brown (10 YR 2/2) silt loam, high in organic matter; very moist; very friable; scattered large rocks 13 cm, roots common; boundary clear and smooth.
5-10	A12	Very dark-brown (10 YR 2/2) loam with some fine to medium sand; somewhat loose and friable; moist; breaks to weak, coarse aggregates; roots common; scattered large rocks as above; boundary clear and smooth.
10-18	B1	Dark-brown (7.5 YR 3/2) organic loam; massive; moist; breaks to moderate, coarse angular blocky and granular structure; roots abundant; boundary abrupt and wavy.

18-30	B12	Dark-brown (7.5 YR 3/2) coarse sandy loam; strong, coarse granular structure; fine roots common; boundary clear and wavy.
30-43	B22	Dark-brown (10 YR 3/3) sandy loam and gravel; massive; structureless to very weak, fine subangular blocky structure or aggregates of sand grains; yellowish-brown (10 YR 5/4) ped coatings; fine roots common; boundary clear to abrupt and wavy.
43-55	C	Pale-brown (10 YR 6/3) gravelly sandy loam moderately well indurated; coatings of very dark grayish brown to dark brown (10 YR 3/2-3/3) and occasional flecks of reddish yellow (7.5 YR 6/6); rock fragments, 90%; many fine gravel fragments completely decomposed; much of the rock fragment material is volcanic; roots absent.

As already noted, strong winds have severely eroded upland positions that at one time very likely had "c" soils developed on them. Both the "c" soils and the truncated soils (see the following paragraph) are included in a single map symbol (maps I to IV in the pocket at the back of this volume) since both are considered Typic Cryan-

depts. The degree of profile truncation ranges widely from simple removal of the A horizons to removal of all genetic horizons, leaving only unmodified parent material (Fig. 10).

The finer textured truncated soils are subjected to frost heaving, as evidenced by the development of small sorted circles and the vesicular character seen commonly in many subsurface horizons.

An example of a truncated profile follows:

Vegetation:		Scattered <i>Carex</i> spp., <i>Empetrum nigrum</i> , <i>Salix</i> sp., and <i>Thamnotia vermicularis</i> . Coverage at site, 40%; coverage of general area ranges between 10 and 40%.
Topography:		Crest area, lag gravel surface; slope angle, 0°.
Microrelief:		Lag fragment size averages 20 cm (range, 8 to 30 cm). Occasional vegetation hummocks 8 to 30 cm.
Drainage:		Well drained.
Depth, cm	Horizon	
0-5	B21	Very dark grayish-brown (10 YR 3/2) loam; moist; massive to slightly friable; organic matter less than 10%; rock fragments 10% in 3- to 8-cm range; roots common; no carbonate reaction, boundary clear and wavy.
5-13	B22	Dark-brown (10 YR 3/3) loam; massive; moist;

Fig. 10—Lag-gravel surface typical of the upland plateau, physiographic region VI. Soil "c" occurs beneath heath-willow vegetation. Truncated soils are found beneath lag-gravel surface. Elevation is approximately 200 m (656 ft).

		breaks to weak, coarse sub-angular blocky structure; very coarse sand and granular material less than 20%; pebble fragments less than 15%; roots common; boundary clear to abrupt and wavy.
13-25	B23	Dark-brown to dark yellowish-brown (10 YR 3/3-3/4) silt loam; very moist; granule material, 10 to 15%; skeleton, 80%; silt loam and granules act as matrix in skeleton; clay coats on skeleton; granules are moderately to strongly weathered; fine roots common; boundary abrupt and wavy.
25-38	C1	Dark-brown (10 YR 4/3) silt loam; drier than above horizon; massive; soil acts as matrix in coarse rock fragments (90%) in 2- to 10-cm (0.8- to 4-in.) range; some void space; clay coats on upper surface of rock fragments; roots absent; boundary gradual and irregular.
38+	R	Fractured bedrock, approximately 4% void space; small amounts of silt loam in voids.

Entisols

Soils included within the order Entisols show little or no evidence of the development of pedogenic horizons. In some of these soils sufficient time has not elapsed to permit the soil-forming processes to develop horizons. In other soils their site of formation is too unstable to allow the development of horizons. The instability may be in the form of active erosion on steep slopes, deflation, frost churning, or the frequent addition of sediment.

On Amchitka Island the stabilized sand dunes and/or sand accumulations so well developed on the coastal bluff in region III and on the west end of the island are the principal areas in which Entisols ("e" soils) are found. Individual pedons of these soils certainly occur on the deflation pavements but have not been separated out from the Inceptisols on maps I to IV in the pocket at the back of this volume.

The sand accumulations on and along the coastal bluffs are composed of coarse to fine sands derived from weathering of volcanic deposits and deposited by strong winds (Everett, Chap. 8, this volume). Additions of sand to most of these sites are infrequent so long as the steep cliff faces retain a turf. When the turf is removed, sand deposition

on the top of the cliff resumes. The soils are well drained, and both the moisture-holding capacity and the field moisture are low. The soils support a dense rank cover of *Elymus arenarius* together with *Lathyrus* sp. and *Senecio* sp. as associates. These plants, especially *Elymus*, contribute a thick litter.

The sandy texture of the Entisols places them in the suborder of Psamments. The following profile is typical for Amchitka and falls within the Typic subgroup of Cryopsamments.

Classification:		Typic Cryopsamment.
Vegetation:		<i>Elymus arenarius</i> , <i>Lathyrus</i> sp. grass, and <i>Senecio</i> sp.
Topography:		Bluff area along north coast 7° (variable); stabilized sand dune.
Microrelief:		Slightly hummocky under vegetation.
Drainage:		Well drained.
Depth, cm	Horizon	
13-0	01	Largely dead and somewhat decomposed leaves and stems of <i>Elymus</i> ; boundary abrupt, smooth.
0-8	A1	Dark reddish-brown (5 YR 2/2) loamy medium sand; high in organic matter; somewhat massive to structureless; roots abundant; boundary clear and smooth.
8-15	A12	Very dark-brown (10 YR 2/2) loamy medium sand; massive; structureless; boundary clear and smooth.
15-25	A13	Black to very dark-brown (10 YR 2/1-2/2) slightly loamy sand; loose; moist; single grained to having a very weak coarse aggregate structure; roots abundant; boundary clear and smooth.
25-75+	C1	Black to very dark-brown (10 YR N2/-2/2) sand; moist; single grained; roots few.

SOIL PHYSICAL PROPERTIES

Bulk Density

Average dry-weight bulk density values representative of the organic or organic-rich portions of soils "a1," "a2," "b," and "bh" are given in Table 1. The progressive increase in bulk density correlates with a systematic decrease in organic carbon content (Appendix A, Table A.1) and to some degree an increase in state of decomposition of the organic matter from bottom to top along the toposequence.

Dry bulk densities were also determined for a limited number of the "c" and "e" soils. Those for

Table 1—Average Field Soil Moisture and Dry Bulk Density for Four Soils of Amchitka Island, Alaska

Soil	Slope angle, °	Range in moisture,* %	Average moisture,* %	Number of analyses	Bulk density, g/cm ³
"a1"	0 to 5	790 to 2640	1256	12	0.09
"a2"	3 to 10	320 to 1260	620	61	0.16
"b"	3 to 33	160 to 932	354	37	0.26
"bh"	2 to 15	104 to 400	201	58	0.36

*Moisture values as percent water, dry-weight basis.

the A horizons of the "c" soil averaged 0.58 g/cm³, and the average dry bulk density of the B horizons was 0.95 g/cm³. Bulk densities for the sand-dune ("e") soils averaged 1.1 g/cm³. In the upper portions of these soils, bulk densities were slightly less owing to the organic-matter inclusion.

There exists a weak but general correlation between bulk density and shrinkage such that for a given volume soil horizons with bulk densities ranging between 0.16 and 0.23 g/cm³ shrank between 70 and 80% after drying for 24 hr at 105°C. This in part reflects the large amorphous and gel component of the soils. The "c" soils with their higher dry bulk densities (indicating an increase in decomposition state of the organic fraction and the increased mineral inclusion) shrank 55% or less. Horizons with dry bulk densities less than about 0.10 g/cm³ showed little or no shrinkage.

Moisture

Just as the principal soil types can be differentiated by their bulk densities so can they also be differentiated by their field moisture contents (Table 2). The moisture contents are closely related to the decomposition state of the organic matter and to the amount of amorphous material in the soil. Soil moisture for a given soil type appears to remain relatively constant throughout the summer growing season. Except for the "c" and "e" soils, soil moisture also remains at or close

to saturation during this period (compare Tables 2 and 3). These findings are probably generally applicable throughout the year.

Table 3—Saturated and Actual Field Moisture for a Soil Toposequence in Region III

Soil	Field moisture,* %	Moisture percent at saturation
"a2"	1160	1220
"b"	168	180
"bh"	122	156
"c"	208	276

*Values determined on the same day, August 1968.

Hydraulic Conductivity

Hydraulic conductivity, which is a measure of the rate of fluid transmission, was determined for three soil types (Table 4). It is clear from the table that there is a marked difference in the rate of

Table 4—Selected Saturated Hydraulic Conductivity (K) for the Principal Organic Soils

Soil	K, cm/hr	Range, cm/hr
"a2"	9.53	Not established
"b"	3.02	Not established
"bh"	1.13	0.40 to 2.30

Table 2—Field Soil Moisture for a Toposequence in Region II

Date	Percentage of moisture*			
	"c"	"bh"	"b"	"a2"
7/18/68	64	133	187	1090
7/24/68	89	153	213	1233
7/31/68	101	149	201	1097
8/7/68	72	123	169	1234
8/29/68	64	147	170	1260

*Moisture values as percent water, dry-weight basis.

water transmission among the soils. The decrease in hydraulic conductivity with elevated position in the toposequence is related to increased bulk densities, which is a function of higher mineral contents and higher decomposition state of the organic component. This, of course, results in compaction and a decrease in both porosity and permeability.

Marked contrasts in hydraulic conductivity may occur between vertical and horizontal directions in the A horizons of the "bh" and "b" soils.

In almost all cases the vertical conductivity exceeds the horizontal, and the limited number of analyses suggests a range of difference from a few percent to as much as 70%.

Samples of A horizon material which contain a natural structural crack show anomalous hydraulic conductivity values, 10.67 cm/hr in one case. Structural cracks, which are common in "bh" and, to a lesser extent, "b" soils, provide avenues for the transmission of considerable quantities of water, vertically as well as horizontally in an otherwise relatively impermeable soil column.

Temperature

The soils of Amchitka are cold. On the basis of the criteria given in the National Soil Taxonomy (Soil Survey Staff, in press, and as outlined on page 181), they are all within the Cryic temperature regime. All midsummer July–August temperatures down to an average depth below the surface of 0.75 m (1 ft) are above the mean annual air temperature for the island, 3.9°C (Armstrong, Chap. 4, this volume). In early September, at a depth of 2 m (6 ft), a temperature of 7°C was recorded. At this depth mineral-soil temperatures generally reflect closely the mean annual air temperature.

Temperature measurements averaged from specific depths in soils along a toposequence as well as from numerous individual profile, upper horizon, temperatures recorded throughout the month of August in 1968 indicate that soils at the wet end of the toposequence, "a1" and "a2," were coolest (8 to 9°C) and "h" and "c" soils at the dry upper end were warmest (10 to 11°C or more). The "b" and "bh" soils were intermediate (9 to 10°C). This distribution of soil temperatures along the toposequence is thought to override the effect of important variables, such as aspect and preceding local weather, and reflects the unique physical characteristics of the different soils.

Mineralogy

In addition to the disaggregation and mechanical fractionation of the mineral component of mineral horizons of the "b," "bh," and "c" soils (Appendix A, Tables A.1 and A.2), special attention was given to the three thin volcanic ash horizons that are present in most "a2" and "b" profiles. As already noted, these horizons or layers are surprisingly consistent in occurrence and depth over the island.* The uppermost ash layer occurs at

an average depth of 15 cm (6 in.) [range 10 to 20 cm (4 to 8 in.)]. The second and third ash layers generally occur in the interval between 23 and 38 cm (9 and 15 in.) [31-cm (12-in.) average] and are separated from one another by 1 to 2 cm of organic material. The upper two layers are of sandy texture and the third generally has the texture of a silt loam.

In thin section the upper two mineral horizons, first and second ash layer, are composed of individual corroded twinned feldspar grains and some highly altered orthopyroxenes. By far the largest proportion of the mineral material consists of rounded and subrounded units of amorphous material with abundant oriented small (45 μ m) feldspar laths. Small vesicular fragments (pumice?) are also common. In general, the ash is andesitic and is primary, i.e., it has not been reworked extensively.

In the second ash layer, pumice(?) fragments are less abundant and plagioclase feldspar laths are smaller and somewhat more corroded than in the upper layer. Pyroxenes are also more abundant, and all show alteration.

The third, or lowest, ash layer also appears to be andesitic but is highly weathered. There are few identifiable plagioclase crystals, and pyroxenes are few and highly altered. Pumice(?) fragments appear weathered and are heavily coated with organic material and iron compounds.

The depth of the ash layers as well as the relative distance between them decreases from the "a2" soils to the "b" soils. This may be due to the lower accumulation rate of organic material in these soils as well as to compaction associated with increased humification.

It is possible that ash landing on "bh" soil positions was washed or blown downslope to "a2" and "b" positions, which would explain its general absence in "bh" profiles. In any event the ashfalls were light and probably had little effect on the vegetation. They were most certainly cold. Slightly thicker ash layers in the island's western regions suggest a western source. If suitable dates are obtained on organic material associated with the ash layers, they will prove useful in the calculation of the rate of organic-matter accumulation, especially in the "a2" soils. On the basis of texture and thin-section analyses (weathering state) alone, there seems to be a significant time difference between the deposition of the lower ash layer and the two subsequent ones.

In addition to the petrographic analyses of the ash layers, clay mineralogical analyses by X-ray diffraction were performed on plated clays separated from the B horizons of several "b," "bh," and "c" soils as well as from the truncated soils

*Other deeper ash layers are commonly encountered in "a2" soils. The three most common of these occur at 73, 90, and 175 cm (28, 35, and 68 in., respectively).

from regions III, IV, and V. Initial X-ray patterns were difficult to interpret. Diffuse peaks in the 14 Å region appeared on air-dry analysis. After glycolation of these clays, they expanded to 16 Å; upon heating to 500°C, they collapsed to a diffuse region between 11 and 13.5 Å. This indicated an expanding lattice clay of montmorillonite type. Failure to collapse completely upon heating suggests the presence of an amorphous constituent, such as organic matter (producing a diffuse peak) or interlayer iron or aluminum holding the lattice apart. All samples were treated with $\text{Na}_2\text{S}_2\text{O}_4$ (sodium dithionite) to remove iron, and the diffractograms were rerun. Iron removal enhanced the characteristic montmorillonite peak and allowed collapse to about 10 Å upon heating to 500°C.

X-ray analysis of the mineral material of the B horizons of typical "b" and "bh" soils showed montmorillonite to be the only clay mineral present. On the basis of the small number of samples analyzed, the relative amount of montmorillonite appears to be 2 to 10 times as great in "bh" soils as it is in "b" soils. This may reflect greater weathering in these better-drained and more-oxidized soils. It may also in part account for their tendency toward solifluction. Small amounts of clay-size quartz and feldspar were also recorded on the diffractograms.

Diffractograms of mineral horizons of "c" and truncated soils showed small amounts of clay-size quartz and feldspar and only trace amounts of montmorillonite. Any pedogenic montmorillonite may have been removed by deflation. Trace amounts of kaolinite(?) were found.

Montmorillonite was identified from a mineral-soil sample taken from a solifluction terrace in region IV. Terraces in regions IV and V probably contain large amounts of this mineral, which in part accounts for their mobility. Much of the montmorillonite in these regions is probably a product of hydrothermal alteration and is not pedogenic.

SOIL CHEMICAL PROPERTIES

Reaction (pH)

Soil profiles of Amchitka Island are moderately to strongly acid throughout (Appendix A, Table A.1). The reduced value of the salt solution pH (KCl) is not very great even into the mineral horizons lying beneath the organic materials. This suggests that there is little hydrogen being held in the soils and that nearly all the hydrogen is exchangeable.

The "c" soil shows a progressively large discrepancy between H_2O and KCl pH with depth,

especially in the B22 and C horizons. This becomes marked below the surface horizon in the representative of the truncated soil. The disparity between the values suggests that a considerable amount of hydrogen is weakly held on the finer fraction and that the lower horizons of the "c" soil and most of the truncated soil have not been leached to any significant degree. If this interpretation is correct, it supports the idea that truncation may be a rather recent phenomenon. The effect of frost churning, which may expose unweathered materials at the surface, cannot be ruled out, but the continuity of horizons would argue that it is not great.

Organic Matter

The organic matter of the island's soils ranges in amount and physical characteristics in a predictable fashion along the toposequence-moisture gradient. The quantity of organic matter (expressed as organic carbon) is found to decrease along the toposequence from the Histosols ("a1" and "a2" soils) where it averages close to 45% to the better drained mineral soils. Organic-carbon values may reach 40% in some horizons of the "b" soils (Cryaquepts), especially where they appear to be transitional to the "a2" soils. Higher in the toposequence the relatively well drained Andic Cryaquepts ("bh" soils) and Cryandepts ("c" soils) may still have an appreciable organic component in their A horizons ranging to 20% in one case. Below the O horizons of the Cryopsamments, organic carbon is quite low.

Exchangeable Cations

The amount of exchangeable cations (calcium, magnesium, sodium, and potassium) in each of the soils is closely linked to the amount of organic matter (organic carbon). Contrast the ash-layer horizons with surrounding organic horizons in the "a2" soil (Appendix A, Table A.1). The influence of the cation-exchange capacity (CEC) increases with the higher states of decomposition (increased amorphous component) in "b" and "bh" soils.

If we compare the observed clay mineralogy with CEC data (summation of the cations), it is apparent that, if the CEC is calculated per unit of clay, assuming a CEC of 300 meq/100 g of carbon for the organic component (Helling et al., 1964; L. P. Wilding, unpublished data), a substantial amorphous component must be present in addition to montmorillonite and organic matter to produce values of 238 meq/100 g for "b" and "bh" soils. An alternate or additional possibility is that the coarser mechanical fractions are contributing significantly to the CEC.

The ratios of calcium to magnesium for all soils (Appendix A, Table A.1) are very narrow, usually less than 1.0, and are typical of acid soils.

The limited amount of data on free iron oxide obtained for the "b" and "bh" soils (Appendix A, Table A.1) shows an increase in the B2 horizon over the C horizon, which suggests iron deposition in these better-drained soils. Very possibly much of the iron was moved down in the profile associated with humic materials.

EVOLUTION OF THE ISLAND'S SOILS

During the last full-glacial period, Amchitka Island probably supported a thin and relatively inactive ice cap that may have completely covered the island. In response to climatic warming, the ice began to shrink, first exposing the uplands and then areas peripheral to the coast. It is unlikely that the formation of organic and organic-rich soils began immediately on retreat of the ice. As Mickelson and Borns (1972) have shown, organic-matter accumulation may not begin for 2000 years after deglaciation. A number of exposures on widely separated parts of the island indicate that after ice recession a periglacial climate prevailed in which mass-wasting and patterned ground formation occurred.

As shown in Fig. 11, a section near Cannikin Lake records events prior to the development of the island's organic soils. It shows a wedge of colluvial sands and gravels lying against a highly weathered bedrock prominence. The materials composing the sediment wedge fine upward and eventually interfinger with bedded silts and clays. These fine-grained deposits contain abundant and well-preserved sedge fragments near their upper boundary which represent the beginning of organic-matter accumulation. A similar sequence is recorded on the Pacific coast west of Rifle Range Point and at drill site E (155 m above sea level) where crudely bedded fine-grained sediments containing diatoms and plant fragments rest on a lag gravel surface (Everett, 1971b).

The organic component of the silts and clays increases upward until between 1 and 2 m below the present surface (depending on the site) a truly organic deposit (peat) occurs. At this point the "a2" (and possibly some "a1") soil began to form. The oldest record of organic-soil accumulation on the island is $10,550 \pm 160$ years B.P. (Everett, 1971b). Two other relatively old dates, 9810 ± 160 and 9200 ± 130 years B.P., were recorded from basal organic layers elsewhere on the island (Holmes and Narver, Inc., personal communication), and a date of 7260 ± 110 years B.P. was obtained from the base of the "a2" soil in Fig. 11.

Fig. 11—Fault scarp produced by Cannikin event. Section shows wedge of colluvial material (A) overlying weathered bedrock (B). Bedded silts and organic matter (C) rest on fine-grained colluvial sediments. Approximately 2.5 m (7 ft) of hemic peat (soil "a2") (D) overlies colluvial sediments. Organic deposits wedge out toward the crest and the soil changes from "a2" to "bh" (E). Bedrock is shallow below the surface at (F). A radiocarbon date of 7260 years B.P. was obtained from organic materials at (G).

Other radiocarbon dates from basal peats in deep sections from Peninsular Alaska and the Prince William Sound area fall within the range $8870 \pm 10,390$ years B.P. (Heusser, 1959). It seems clear that the inception of peat formation on Amchitka Island was a late glacial or early post-glacial event and was probably concomitant with a regional phenomenon in the North Pacific area.

The highly organic soils that occur topographically above and commonly grade into the "a2" soils, i.e., the "bh" and "b" soils, also represent organic and organic-mineral accumulations under a cool maritime climate. Fluctuating or seasonal water tables have permitted more complete oxidation of the organic residues as well as provided for translocation of humic acids and organo-mineral chelates (iron and aluminum) downward in the profile. Their precipitation at and within the coarser textured subsolum has produced humiluvic and indurated horizons. Such soils, especially the "bh" soil, have many characteristics in common with podzolized soils of the alpine regions. FitzPatrick (1964) considers soils in Scotland with apparently similar characteristics as Podzols with extreme development of the A horizon.

Little is known concerning the development of Folist soils. Those of Amchitka ("h" soils) occur on felsenmeer surfaces and probably could not have begun to develop until cessation of intensive periglacial conditions in the island's highland area.

Under the present climate of the island, the production and accumulation of organic matter and the further development of organic and organic-rich mineral soils are apparently continuing, at least in areas below 100 m (300 ft). Above this elevation there are numerous indications of a once-more extensive organic soil cover. These soils are in the form of organic-rich mineral soils that have and apparently are being removed by a combination of frost heaving, wind stripping, and water erosion. The balance point between the formation and destruction of these soils is probably a delicate one, strongly controlled by the freezing intensity and the number of freeze-thaw cycles. The available although meager evidence suggests that it is shifting toward lower elevations.

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APPENDIX A: SELECTED CHEMICAL AND PHYSICAL ANALYSES

Methods of Analyses

Exchangeable calcium and magnesium (EDTA method of H. L. Barrows and E. C. Simpson, 1962, *Soil Sci. Soc. Amer., Proc.*, 26: 443-445).

Exchangeable potassium (flame spectrophotometric analysis of neutral normal NH_4OAc leachate).

Exchangeable sodium (flame spectrophotometric analysis).

Exchangeable total bases (sum of exchangeable calcium, magnesium, sodium, and potassium).

Estimation of free iron oxides (method of Victor S. Kilmer, 1960, *Soil Sci. Soc. Amer., Proc.*, 24: 420-421).

Organic carbon (dry-combustion method for which the procedure and apparatus used were similar to that described by C. S. Piper, 1947, *Soil and Plant Analysis*, pp. 216-233, Interscience

Publishers Inc., now John Wiley & Sons, Inc., New York).

Reaction (pH) (method reported by Michael Peech et al., 1947, U. S. Department of Agriculture, Circular No. 757, p. 5).

Particle-size distribution analysis (pipet method modified from that of J. G. Steele and R. Bradfield, 1934, American Soil Survey Association Bulletin No. 15, pp. 88-93. Organic-matter removal using hydrogen peroxide and dispersion using sodium hexametaphosphate).

Ignition loss (percentage of sample weight lost by heating to 550°C for 2 hr).

Selected Chemical Data

Because the soils information was collected over several years and under different funding levels, the profiles selected to represent the modal soil may not correspond to chemical and physical data obtained on similar soils. Unless otherwise noted, all chemical data are reported on an oven-dry 105°C basis.

Table A.1—Selected Soil Chemical Data*

Horizon	Depth, cm	pH		Weight loss on ignition, %	Organic carbon, %	meq/100 g						Sum cations, meq/100 g	Sum bases, meq/100 g	Base saturation, %
		H ₂ O	KCl			Fe ₂ O ₃	H	Ca	Mg	Na	K			
"a1" Soil (Typic Cryofibrst)														
Oa1	0-5	5.0		89.7	41.7	48.2	17.4	23.9	3.9	2.08		95.5	47.3	50
Oe1	5-10	4.7		92.0	48.7	74.1	12.8	17.7	3.3	1.55		109.5	35.4	32
Oi1	18-25	4.8		84.2	44.9	103.5	7.2	9.4	2.6	0.44		123.1	19.6	16
Oi2	25-51	4.7		94.2	53.9	131.4	8.2	8.8	2.2	0.26		150.9	19.5	13
Oi3	51-55	4.8		83.8	42.9	119.6	10.2	8.3	2.1	0.14		140.3	20.7	15
Oe2	55-57	4.9		17.4	9.1	36.0	1.4	1.4	0.5	0.02		39.3	3.3	8
Oi4	57-67	5.0		86.2	44.0	98.9	8.8	6.9	1.9	0.10		116.6	17.7	15
Oi5	67-85	5.1		76.7	41.1	80.6	8.5	6.9	2.2	0.11		98.3	17.7	18
"a2" Soil (Fluvaquentic Cryohemist)														
Oe1	3-0	4.3	3.8	91.6	46.5	60.0	3.8	8.2	2.40	1.85		76.3	16.3	19
Oe2	10-25	4.5	3.9	92.1	46.3	52.0	2.1	4.1	2.03	0.45		60.7	8.7	11
C1	25-28	4.7	4.3	21.8	11.8	31.2	0.4	1.3	1.15	0.14		34.2	3.0	
Oa2	28-47	4.5	4.1	89.3	48.6	41.8	2.1	4.1	1.72	0.29		50.0	8.2	13
Oe3	47-55	4.6	4.0	92.5	51.0	41.6	3.2	5.2	1.84	0.29		52.1	10.5	17
Oe4	55-105	4.6	4.3	82.4	45.6	31.4	2.8	3.6	1.25	0.15		39.2	7.8	17
C2	68-75	5.2	4.7	25.8	13.5	43.2	1.1	0.7	0.61	0.08		45.7	2.5	
Oi2	105-115	5.0	4.4	70.3	38.9	42.4	2.3	2.9	0.97	0.11		48.7	6.3	11
Oi3 and 4	115-158	4.7	4.3	84.1	46.7	29.6	2.7	3.1	0.59	0.10		36.1	6.5	17
Oi5	158-175	5.0	4.5	90.9	49.8	33.3	7.1	4.3	1.00	0.14		45.8	12.5	25
"b" Soil† (Andic Cryaquept)														
O1	0-5	4.2	3.8	80.4	41.6	57.7	5.1	8.3	1.32	1.77		74.2	16.5	22
O2	5-15	4.3	4.0	73.5	39.0	34.3	1.3	3.9	0.91	1.39		41.8	7.5	18
C1	18-20	4.8	4.4	20.9	11.6	37.4	0.2	1.0	0.35	0.27		39.2	1.8	5
O3	20-30	5.0	4.4	55.8	30.4	48.9	0.3	1.5	0.60	0.65		51.9	3.0	6
HC2	30-38	4.7	4.6	19.4	8.5	38.3	0.1	0.3	0.23	0.19		39.1	0.8	2
A11	38-63	4.8	4.8	24.8	10.8	37.8	0.0	0.6	0.34	0.24		38.9	1.2	3
A12	63-68	4.8	4.6	57.3	31.5	38.8	0.0	1.4	0.56	0.21		41.0	2.2	5
B2	68+	5.1	4.6	10.0	3.1	34.8	0.4	0.7	0.58	0.50		37.0	2.2	6
"bh" Soil†,‡ (Andic Cryaquept, Hummock Phase)														
A1	0-3	4.8	3.8	55.1	29.6	54.7	4.4	8.2	1.46	1.88		70.6	15.9	23
A12	3-5	4.3	4.1	39.7	20.0	61.2	1.5	4.7	0.56	1.27		69.2	8.0	12
A13	5-11	4.6	4.2	38.0	19.4	70.5	0.8	3.2	0.47	0.70		75.7	5.2	7
A14	11-20	4.9	4.5	38.6	19.4	92.6	0.4	1.3	0.54	0.63		95.5	2.9	3
A15	20-30	5.1	4.6	38.1	18.8	66.8	0.5	1.8	0.54	0.72		70.4	3.6	5

Table A.1—(Continued)

Horizon	Depth, cm	pH		Weight loss on ignition, %	Organic carbon, %	meq/100 g						Sum cations, meq/100 g	Sum bases, meq/100 g	Base saturation, %
		H ₂ O	KCl			Fe ₂ O ₃	H	Ca	Mg	Na	K			
A16	30–45	4.9	4.6	28.7	11.9		54.9	0.0	1.3	0.65	1.64	58.5	3.6	6
B22	45–48	5.0	4.6	16.2	6.6		49.4	0.1	0.7	0.80	1.84	52.8	3.4	6
B23	48–63	4.7	4.8	9.0	1.5		33.8	0.3	1.1	0.87	2.34	38.4	4.6	12
"b" Soil (Dystric Cryandept)														
A31	23–35	5.6	4.5	12.6	6.4									
A32	35–40	5.7	4.8	25.3	10.1									
A33	40–45	5.7	4.8	21.1	7.8									
B11	45–58	5.6	4.8	21.1	8.0									
B12	58–63	5.4	4.9	18.1	7.6	5.1	49.3	3.1	5.1	0.35	0.11	57.9	8.6	15
B21	63–73	5.2	4.7	14.8	6.4	5.8	54.3	4.2	5.7	0.39	0.15	64.7	10.4	16
B22	73–83	5.2	4.8	9.8	4.9	2.1	45.6	3.4	5.8	0.30	0.10	55.2	9.6	17
"c" Soil† (Typic Cryandept)														
A1	0–5	4.2	3.9		26.5		53.3	4.0	6.9	1.25	1.12	66.6	13.3	20
A12	5–10	4.5	4.2		14.4		50.6	1.9	3.7	0.86	0.71	57.8	7.2	12
B1	10–18	5.0	4.5		9.2		44.8	1.6	2.6	0.57	0.38	50.0	5.2	10
B12	18–30	5.1	4.6		4.1		32.9	1.1	1.8	0.46	0.33	36.6	3.7	10
B22	30–43	5.5	4.6		2.0		26.9	0.9	2.1	0.46	0.33	30.7	3.8	12
C	43–55	5.4	4.5		0.9		20.2	1.1	2.7	0.57	0.44	25.0	4.8	19
Truncated Profile														
B21	0–5	5.7	5.1	6.8	2.3	1.4	18.6	3.2	6.1	0.23	0.44	28.6	10.0	35
B22	5–13	6.0	5.2	8.1	2.5	1.2	25.7	4.8	7.5	0.21	0.44	38.7	13.0	34
B23	13–25	6.2	5.4	8.3	2.4	1.4	30.1	10.9	15.8	0.33	0.68	57.8	27.7	48
C1	25–38	6.2	5.4	6.0	1.3	1.5	25.3	20.2	48.4	0.82	1.41	96.1	70.8	74

*Unless otherwise noted, all chemical data are reported on an oven-dry (105°C) basis.

†Analytical data from a profile other than text description.

‡Samples analyzed at field moisture, values corrected.

Table A.2—Selected Mechanical Analyses (Percent Distribution in Indicated Particle Size, mm)

Horizon	Depth, cm	Sand*						Silt				Clay			Texture class†
		VCS	CS	MS	FS	VFS	Total	2–5	2–20	20–50	Total	0.2	0.2–2	Total	
"b" Soil* (Andic Cryandept)															
B2	55–65	2.9	3.2	1.8	7.2	13.6	28.7	12.1	32.9	16.0	48.9	0.7	21.7	22.4	L
B23	65–77	8.4	7.4	4.2	9.0	11.3	40.3	8.4	29.8	14.1	43.9	0.2	15.6	15.8	L
"bh" Soil‡ (Andic Cryandept, Hummock Phase)															
B2	45–48	3.9	8.2	5.4	12.4	15.4	45.3		31.8	12.5	44.3	0.3	10.1	10.4	L
B23	48–63	8.5	15.0	8.2	13.6	11.3	56.6		28.9	10.9	39.8	0.2	3.4	3.6	SL
"b" Soil (Dystric Cryandept)															
Oa1	5–10	7.3	8.7	3.9	6.7	8.3	34.9	5.4	15.7	38.7	54.4	6.8	3.9	10.7	SiL
Oa2	10–23	12.6	12.5	5.1	10.8	8.9	49.9	4.0	15.4	24.8	40.2	5.0	4.9	9.9	L
A31	23–35	8.9	10.6	5.8	11.9	10.1	47.3	4.0	16.4	24.7	41.1	3.1	8.5	11.6	L
A32	35–40	0.7	3.6	14.5	19.8	6.2	44.8	2.9	12.5	28.5	41.0	4.0	10.2	14.2	L
A33	40–45	1.8	6.4	4.8	13.8	10.7	37.5	6.2	21.6	27.3	48.9	3.4	10.2	13.6	L
B11	45–58	1.4	6.3	5.2	12.4	11.4	36.7	5.5	18.5	30.9	49.4	3.2	10.7	13.9	SiL
B12	58–63	1.6	6.8	6.5	17.0	12.2	44.1	6.6	21.7	19.7	41.4	3.6	10.9	14.5	L
B21	63–73	4.6	8.0	6.0	17.2	14.1	49.9	6.2	26.8	9.9	36.7	2.6	10.8	13.4	L
B22	73–83	18.0	14.1	5.8	12.1	9.9	59.9	4.8	17.6	12.2	29.9	3.5	6.7	10.2	SL
"c" Soil (Typic Cryandept)															
A1	0–5	1.3	3.7	3.3	11.7	6.5	26.6		22.2	37.1	59.3	5.6	8.2	14.1	SiL
A12	5–11	1.8	4.1	6.1	16.4	10.6	39.0		22.1	24.6	46.7	4.0	10.3	14.3	L
B1	11–18	7.5	9.5	7.7	15.3	9.6	49.6		23.4	14.9	38.3	2.1	10.0	12.1	L
B12	18–30	8.8	13.0	8.3	17.5	11.4	58.9		22.2	10.1	32.3	2.0	6.8	8.8	SL
B22	30–43	5.5	15.5	10.1	21.6	14.4	67.0		16.5	10.6	27.1	1.4	4.5	5.9	SL
C	43–55	10.2	19.3	9.0	17.3	12.6	68.4		17.4	10.0	27.4	1.1	3.1	4.2	SL
Truncated Profile															
B21	0–5	8.6	7.4	6.1	11.1	16.6	49.8	6.3	28.2	14.1	42.3	0.4	7.5	7.9	L
B22	5–13	8.9	11.0	6.2	11.4	12.0	49.5	6.3	26.5	14.1	40.6	0.4	9.5	9.9	L
B23	13–25	4.3	5.3	5.1	10.9	14.9	40.5	8.0	28.2	22.0	50.2	0.0	9.3	9.3	SiL
C1	25–38	2.4	2.3	2.3	7.0	15.4	29.4	12.2	50.5	12.2	62.7	0.5	7.4	7.9	SiL

*VCS, very coarse sand; CS, coarse sand; MS, medium sand; FS, fine sand; VFS, very fine sand.

†SiL, silt loam; L, loam; SL, sandy loam.

‡Analytical data from a profile other than text description.

APPENDIX B: SOILS MAP PREPARATION

The soils maps were prepared for Amchitka Island (maps I to IV in the pocket at the back of this volume). After the principal soil groups and their ranges in characteristics had been established, detailed traverse mapping was carried out on standard 1 : 26,000, 22.5- by 22.5-cm Coast and Geodetic Survey air photographs taken in 1948. At least one traverse was made over the area covered by each photograph. Each traverse was conducted so that it covered the range of topographic elements in the area. Soil test pits and probes were made at frequent intervals to determine the soil type. Soil boundaries were extended from the traverse line on the basis of stereographic interpretation of photographic tone and topography. These boundaries were further extended and refined on 45- by 45-cm enlargements of the original photographs.

An uncontrolled photomosaic was made for each map. Soil boundaries were transcribed to Mylar using the overlapping central 50% of each photograph to minimize distortion. This procedure was not always possible, however, since the flight lines of the photographic coverage did not always allow sufficient overlap, and in a few cases the only overlap possible was on the distorted periphery. Not all lakes are shown on the maps to minimize confusion with soil boundaries. The road is shown as it was in 1948, prior to recent relocations.

For simplification, the final mapping related soils were combined. For example, the solid yellow color on the maps indicates a soil association in which "b" and "bh" soils together occupy 75% (estimated) of the area and "bh" soils alone account for 50% of the area. Other soils also occur in the area but are clearly subordinate in areal extent.

Terrestrial Plant Ecology

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Amchitka Island, near the western end of the Aleutian chain, has a maritime tundra regime that is reflected in a rather uniform meadow-like vegetation of relatively few plant taxa. The tundra vegetation exists as a continuum of types that fall into definable topoenvironmental units along a moisture gradient from fen to bog with a wind blowout-solifluction zone at higher exposed sites.

The terrestrial vegetation of the island is the primary energy production source used by most of the other organisms in the island ecosystem. Local instability in soil drainage patterns, due in part to slow downslope movement

of the peat-soil mantle, leads to a corresponding instability in vegetative cover in many areas.

Natural revegetation of disturbed areas, which is better described as recovery than as directional secondary succession, can occur within a few years on drained organic substrates but may require a much longer time on mineral soils. Factors responsible for slow rates of recovery where vegetation has been destroyed include a lack of pioneering weedy taxa, frost heaving, lateral instability of the substrates, low availability of seeds or other propagules, and a generally depauperate island flora.

The Amchitka landscape reflects the maritime subarctic regime of the western Aleutian Islands. The tundra vegetational composition and structure indicate the isolation of the island and the generally inclement weather. The vegetation is of low stature, forming a nearly complete meadow-like cover at lower elevations, but it is often discontinuous and dominated by subshrubs at elevations above 70 to 90 m (230 to 295 ft).

Maritime tundra, such as that found in the Aleutian Islands, does not extend over large areas of the world. The natural history of the Aleutians combines with the present climate (characterized by low solar-energy input, generally low temperatures, frequent light precipitation, occasional hurricane force winds, and the influence of the surrounding sea) to produce a rather monotonous vegetation of relatively few vascular-plant species. Published ecological studies on subarctic maritime tundra are few, and long-term investigations are infrequent on such landscapes.

The flora of Amchitka and of the entire Aleutian chain is reasonably well known. As early as 1779 David Nelson collected and identified plants at Unalaska. In 1834, F. V. Wrangell made Aleutian collections on other islands. More recent botanical investigations included visits by Japanese scientists in the 1920s and 1930s. Hultén (1960 and 1968) collected on Amchitka and recorded the history of botanical work in the area. Shacklette et al. (1969) collected bryophytes, lichens, and vascular plants on Amchitka. Nomenclature used in

this project follows that of Hultén (1968) and Shacklette et al. (1969).

The present investigations began in 1967 as part of a bioenvironmental evaluation of Amchitka sponsored by the U. S. Atomic Energy Commission's Nevada Operations Office through a contract with Battelle Columbus Laboratories. The original objectives of the studies of the terrestrial plant ecology included (1) characterization and delineation of important vegetation units, (2) determination of the status and dynamics of the terrestrial ecosystem based on primary producers, (3) inventory and identification of plants, (4) predictions concerning the probable consequences of underground nuclear testing on the plant communities, and (5) determination of the effects of man's activities on the terrestrial vegetation. Objectives 1 to 3 and 5 are examined and discussed in this chapter. Objectives 4 and 5 are discussed in detail in a report by Everett and Amundsen (1975).

This study was initiated by E. E. C. Clebsch in June 1967 with a brief reconnaissance of the island. Starting in September 1967 and continuing in alternate months through October 1968, I carried out a detailed qualitative and quantitative investigation of the terrestrial vegetation. This study included an examination of every major drainage on the island.

Field work was resumed in the spring of 1969 and continued until after the Milrow detonation in October 1969. Assessment of changes in the

terrestrial vegetation was continued during the growing seasons of 1970 and 1971. During this 2-year period, much of the field work was also concerned with the preparation of experimental plots to monitor specific effects of the Cannikin detonation, which occurred in November 1971. A brief assessment of immediate Cannikin effects followed the detonation, and the effects study was resumed in the spring of 1972 and carried through the growing seasons of 1972, 1973, and 1974.

Two closely related projects, funded by the AEC Division of Biomedical and Environmental Research, were carried out in 1971 to 1974. These projects concerned patterns and processes of unmanaged recovery of vegetation on disturbed areas and primary consumption of vegetation.

Robert Kerley and Curtis Richardson assisted in the first year of the studies. Terry S. Chilcoat did most of the work on natural vegetation recovery in 1971 and 1972, and Christopher O'Brien did most of the field work relating to primary consumers during the summer of 1973.

METHODS

Vegetation Sampling

Initial field observations led to the hypothesis that the island vegetation is divisible into three topoenvironmental units: (1) beach, (2) lowland tundra, and (3) upland tundra. A detailed reconnaissance and sampling program to test this hypothesis was started in 1967. The plot sampling program was accomplished with 1-m² quadrats and the abundance-vigor-coverage scale of Domin as modified by Dahl (Evans and Dahl, 1955). A total of 86 quadrats located on several topoenvironmental transects were studied during 1967 and 1968. The results confirmed the topoenvironmental units distinguished during the overall reconnaissance. Additional selective quadrat sampling continued throughout the study and fully supported the unit classification of the terrestrial vegetation.

For the sample quadrats, the vegetation was divided into three strata or synusiae: A, grasses, sedges, herbs, and ferns; B, subshrubs; and C, mosses, lichens, and liverworts. Continued sampling showed this division to be realistic.

Productivity Sampling

Before the 1968 season, 1-m² quadrats were staked out in several of the recognized plant-community types, and all standing dead graminoid, herbaceous, and fern biomass above the level of fresh litter was clipped and removed. These plots were clip-harvested in October 1968 to estimate

the season's production in the A stratum. A few of these plots were similarly harvested following the growing seasons of 1971 and 1972. One plot (the most productive) was also harvested in 1973. All harvested samples were brought to constant air-dry weight in the laboratory. The collecting of all A stratum biomass on a 1-m² quadrat is a painstaking endeavor in the fairly dense vegetation and very windy climatic regime of Amchitka. Small scissors and a well-anchored harvest bag as well as a full rainsuit proved necessary since such plots are best approached from the prone position.

Peat Movement Studies

Calibrated steel soil probes were used to measure the depth of organic soils above bedrock. Six soil-depth grids were taken [probes 5 m (16.5 ft) apart on lines 10 m (33 ft) apart] in six small drainage basins at lower elevations. These measurements indicated that organic-soil depths increased on lower slope positions and decreased across the valley, suggesting a slow downslope movement of the peat substrate over bedrock and subsequent changes in substrate water retention. These indications led to the establishment of six controlled multipoint plots or stations to determine the rate and amount of movement that might affect plant distribution under both ordinary environmental conditions and extraordinary conditions resulting from severe ground shock. All stations were surveyed to points, and vegetation maps were prepared. Regular inspections for movement of points and changes in vegetation were made.

Cannikin Disturbance Transects

Ten permanent quantitative line-intercept transects were established across areas that represented various disturbances to vegetation associated with the Cannikin event (the Milrow test detonation caused very little disturbance to the terrestrial vegetation except at surface ground zero).

These ten transects were established as the result of a brief postshot investigation in November 1971 when the presence of identifiable standing dead vegetation allowed the characterization of the prevalent preshot (1971) plant community.

Other Ecosystem Dynamics Studies

Vegetation Recovery on Disturbed Areas. From July 1971 to September 1972, a study was carried on to detect any pattern or predictable process in the recovery of areas where vegetation had been disturbed. Disturbed areas were classified by type or cause, approximate date of

disturbance, and location. One hundred and three plot complexes of two or more line-point transects each were taken, yielding over 20,000 data points. The data were analyzed to test the hypothesis: There is no directional seral succession in disturbed areas where vegetational recovery is occurring.

Because of the high winds on the island, an ordinary metal or cloth tape could not be used as a line. A 25-m-long brass chain with links painted at decimeter intervals was used instead. Species data were taken by pin "hits" at these links.

Primary Consumers. A short study was done in the summer of 1973 on the consumer impact on the vegetation by the only terrestrial mammal on the island, the Norway rat. Inland sample areas (40 m²) were examined for evidence of trail establishment and nesting and feeding activity. Some 80 rats were collected for stomach-content analyses. Evidence of insect grazing on plants was also sought for evaluation of this aspect of primary consumption.

Plant Species Inventory

Plant sight identifications and collections were made throughout the study, but most of our collections were made in the fall of 1967 and through the growing season of 1968. E. E. C. Clebsch and A. J. Sharp (The University of Tennessee), H. T. Shacklette (U. S. Geological Survey), William Mitchell (University of Alaska), and LeRoy Sowl (Bureau of Sport Fisheries and Wildlife) were helpful in identifications. Voucher specimens of the collection are deposited in The University of Tennessee Herbarium (Tenn.). Duplicate specimens have been sent to other laboratories as requested.

Mapping of Plant Communities

Several aerial photography series of varying areal coverage were available for Amchitka. Vertical black and white photographs (U. S. Coast and Geodetic Survey, 1948) and false-color infrared positives (U. S. Geological Survey, 1968) along with ground-data investigations were used to map six vegetational units on the island, distinguishable on U. S. Army Map Service 1 : 25,000 topographic maps. Reproductions of these maps are included in the report by Amundsen (1972). The approximate areas of the several units were determined by planimetry.

RESULTS

Plant Communities and Topoenvironment

The reconnaissance and subsequent plot sampling and analyses revealed that the vegetation of

the island, not including the beach communities, exists as a structural and compositional tundra continuum along a moisture gradient from fen* to wind-desiccated subshrub-grass stripe communities at the drier and generally higher end of the gradient. For convenience, the maritime tundra ecosystem was divided into two topoenvironmental categories or units: (1) poorly drained lowland and (2) relatively well-drained upland. The beach and dune communities, which are not really tundra, represent a third distinct topoenvironmental entity, although the dominants of the beach and dune grass community (*Elymus arenarius*, *Calamagrostis nutkaënsis*, *Festuca* spp.) are important in and, in fact, dominate certain communities of the tundra vegetation.

Although there is some morphogenetic evidence of a change in environmental dynamics at elevations of approximately 70 to 90 m (230 to 295 ft) (as in the growth form of *Lupinus* and *Salix*), community compositional differences could not be demonstrated quantitatively. The separation of upland and lowland topoenvironments is based on topography and the restriction of drainage rather than on altitude.

Within the 3 topoenvironmental units, 10 plant-community types were recognized as the result of plot sampling (Fig. 1). In the upland tundra units the types are (1) crowberry-grass dominated stripes interspersed with bare areas (Figs. 2 and 3), (2) upland graminoid stands (Fig. 4), (3) secondary-recovery vegetation (Figs. 5 and 6), and (4) crowberry-grass-sedge meadow (Figs. 7 to 9). In the lowland tundra unit the types are (5) crowberry-sedge-grass meadow, (6) sedge-lichen meadow (Figs. 9 and 10), (7) "break-away" tundra (tundra vegetation with cryptogamic cover and scattered weakly rooted plants) (Fig. 10), and (8) ephemeral pools. Community types in the beach-dune unit are (9) beach and dune grass (Figs. 11 and 12), and (10) a community of scattered mostly succulent herbs (Fig. 12).

Areal Extent of Mappable Vegetation Units

Community types were defined and grouped into mappable units. The ten types listed above were determined by reconnaissance and sampling, but the quality of available aerial photography required the grouping of the ten types into six mappable units (Fig. 1).

*A treeless, wet, meadow-like peat flat (Ahti and Hepburn, 1967).

Fig. 1—Community-type distribution along the moisture gradient on the maritime tundra landscape of Amchitka. Numerals following community types group the mapped vegetation units that were inseparable on the available aerial photography.

The beach and dune topoenvironmental unit, which contains two community types, grass stands and scattered succulents, was mapped as a single entity (1). The unit has an approximate area of 4 km².

The wet-tundra map unit (2) includes the ephemeral pool, breakaway tundra, and sedge-lichen meadow types of the lowland tundra. The area as mapped covers approximately 26 km².

The meadow unit (3) includes the crowberry-sedge-grass type of lowland tundra and the crowberry-grass-sedge type of upland tundra. The meadow unit is the largest in extent on the island, covering approximately 154 km².

The upland graminoid community type could easily be detected on the aerial imagery available following ground-data verification. This type (4) was mapped, and the area totaled about 8 km².

Secondary-recovery stands were also easily identified; type (5) was mapped and was found to total about 15 km².

The crowberry-grass stripe type, a topographic expression of upland meadow, is often continuous at higher elevations and is easily plotted. Type (6) was determined to cover 74 km².

(Text continues on page 212.)

Fig. 2—Crowberry-grass-stripe community type on Amchitka. The distance to the peak on the right is about 100 m from the camera. The elevation of the peak is about 350 m mean sea level. Vegetated stripes of crowberry anchor grasses and sedges that grow through the subshrub mat. Aeolian, colluvial, and alluvial processes contribute to a slow usually downslope movement of the vegetation stripes. Nearly barren lag-gravel surfaces occur in very exposed areas, such as the small saddle in the foreground. August 1968.

Fig. 3—Close-up of downslope vegetation scarp in the crowberry–grass–stripe zone on Amchitka. In this instance physical forces are causing an upslope erosion of the vegetation mat, as indicated by exposed roots of *Salix* sp. in the center foreground. The result is a narrower vegetated stripe. Since there is not a prevailing direction on very windy Amchitka, such scarp formation seems almost capricious.

Fig. 4—Lush expression of the upland graminoid community on Amchitka, here dominated by *Calamagrostis nutkaensis*. The organic substrate that supports this community alongside a small swift-flowing stream (riparian) is closing over the stream, and many similar streams have become subterranean because of such movement. The biologists pictured are collecting fish.

Fig. 5—Graminoid recovery on organic soil overturned in 1965. *Deschampsia beringensis* is most common, with certain *Carex* spp. and *Luzula* spp. prominent. The exposed peat blocks are slowly wasting away, and the surface is becoming more regular. Similar recovery is not occurring on mineral substrates that were exposed or stripped of plants during the 1965 activities. August 1974.

Fig. 6—Graminoid recovery on an organic surface stripped by a ground slide at the time of the Milrow detonation, October 1969. *Deschampsia beringensis* is predominant. Crowberry—grass—sedge meadow is the most stable vegetation on moderate slopes such as this, and the establishment of a graminoid cover promotes future stability. August 1974.

Fig. 7—Typical crowberry–grass–sedge meadow on Amchitka. The road berm in the background is of World War II age, and the organic substrate disturbed at that time now supports a closed vegetation of graminoid plants. This photograph is an overview of the community pictured close-up in Fig. 8. July 1972.

Fig. 8—Closeup view of crowberry–grass–sedge meadow. The grass is mostly *Calamagrostis nutkaënsis*. The dense vegetational cover of this community, unlike that of the sedge–lichen meadow, is not easily damaged by occasional traffic of light track pressure vehicles. The extensive root system of the crowberry as well as its resiliency is responsible for this durability. August 1974.

Fig. 9—Topoenvironmental sequence of plant communities from crowberry–grass–sedge meadow at upper slope positions to sedge–lichen meadow at transition of slopes to riparian example of upland graminoid community along Ultra Creek. The crest of the slope facing the observer is about 200 m away. The photograph was taken about 30 m up the slope from the stream. Summer 1968.

Fig. 10—Close-up of undisturbed sedge–lichen meadow community on Amchitka. *Carex* spp., *Juncus* spp., *Rubus* spp., and various Umbelliferae dominate in the vascular-plant strata. *Cladonia* spp. are the most conspicuous cryptogams. This vegetation, in spite of the dense cover, is vulnerable to tracked vehicle traffic and is easily torn away. Annual vascular-plant biomass accumulations average only 31 g/m² in this community. The four stakes delineate 1 m². August 1974.

Fig. 11—The beach-grass community of the beach-dune topoenvironmental vegetation unit at the mouth of Ultra Creek. The bluff at the left is about 12 m above the closed beach community. The beach-grass is mostly *Elymus arenarius* and *Poa* spp. and is over 1 m tall. The underlying substrate is sand. The pole and stakes in the foreground mark a permanent transect.

Fig. 12—Peat calving onto a North Pacific beach on Amchitka. The large organic-substrate blocks are vegetated with *Elymus arenarius* and *Senecio pseudo-arnica*. They will not persist here since the relative bareness of the beach sand indicates rather frequent storm washing. This removal of the organic substrate from the terrestrial ecosystem is an interesting facet of the output from this maritime tundra island.

Maps of vegetation cover, as reduced from U. S. Army Map Service 1 : 25,000 sheets, are included as part of a previous report (Amundsen, 1972).

Vegetation

In 1968 quantitative sampling was done in four community types, and qualitative observations were made in the others. In the upland tundra topoenvironment, 8 quadrats were in the upland graminoid type and 37 were in crowberry-grass-sedge meadow. In the lowland tundra, 35 quadrats were in crowberry-sedge-grass meadow and 6 were in sedge-lichen meadow.

The four community types sampled quantitatively account for about 67% of the terrestrial vegetation of Amchitka. The only other significantly large undisturbed community type is crowberry-grass stripe at higher elevations, which is a topoedaphic expression of the crowberry-grass-sedge meadow. The disturbance-generated secondary-recovery community type contains species typical of the upland unit. Of the 82 species sampled in the plots, 53 were in stratum A, 9 in stratum B, and 20 in stratum C. The Domin-Dahl scale was used to evaluate the abundance-coverage of all species. The Domin-Dahl values were converted to a weighted cover-frequency index value by multiplying the average Domin-Dahl value by percent frequency. The maximum possible index value would be 1000 (Domin-Dahl average of $10 \times 100\%$ frequency), but the highest calculated was 750 for *Empetrum nigrum* (crowberry) in the crowberry-grass-sedge community of the upland tundra. Table 1 gives the index values for all identified species sampled in the four community types. Unidentified cryptogams of insignificant cover or abundance were disregarded. The floristic distinctions separating the community types as well as the continuous relationships between them can be derived from the table.

Plant Species Inventory

Vascular plants representing 46 families were collected and identified during the course of the study. Herbarium specimens were prepared from those suitable for preservation. Vouchers are on deposit in The University of Tennessee Herbarium (Tenn.). Although a complete floristic study was not a primary objective of this project, less than 200 vascular species could be identified after diligent collecting (a relatively poor flora compared to such arctic areas as Cape Thompson, where over 300 vascular species were collected) (Johnson et al., 1966). Shacklette et al. (1969) discussed the flora of Amchitka in detail. Table 2 is a tabulation of

vascular-plant species listed by Shacklette et al. plus eight species not previously reported from Amchitka with notation of collections made for The University of Tennessee project.

Only one established annual higher plant, *Koenigia islandica*, was found in this study. Many of the plants do not regularly produce sexual propagules on Amchitka. It should also be noted that none of the plants found are really robust "weeds" that would significantly alter the microclimate of disturbed areas.

Productivity

Twenty-four plots were harvested over three growing seasons (Table 3), several more than once. One graminoid plot labeled "flush" (nutrient-enriched area owing to the overflow of an upslope lake during storms) had a three-season annual mean yield of 523 g of dry matter per square meter. This primary production compares favorably with that measured in herbaceous ecosystems in other climatic regimes (Kelly et al., 1969, pp. 8 and 9). This plot was harvested once more in 1973 and yielded 467 g of dry matter.

Peat Movement

Results from the six soil probe grids indicated that the deepest organic soil was not always in the lowland valley or stream bottoms but was more often at the lower slope transitions. Figure 13 is a graphic representation of the soil depths and types (Everett, Chap. 9, this volume) and the corresponding plant communities on a normal profile. The depth profiles indicate that a slow slippage or slump of wet peat toward stream bottoms and sea cliffs occurs where the topography of the bedrock contact allows downslope movement. The lesser depths in valleys and stream bottoms suggest that, besides compaction and subsidence, a hydric dissolution of the organic material occurs, and the brownish coloration of many streams indicates that a considerable amount of organic material may be carried in solution and suspension even in streams with low gradients.

As a result of the discovery that slope movement and the control of plant-community distribution were drainage restricted, formal surveys were used to establish six multipoint stations to measure movement and community shifts.

Resurveys and mapping periods were designed to allow some separation of "ordinary" or gravitational movement and extraordinary movement brought about by the shock of the underground nuclear tests.

Three of the multipoint stations (grids) showed slight random changes with no plant-community

(Text continues on page 218.)

Table 1—Cover-Frequency Indexes of Species for Four Major Plant Community Types on Amchitka*

Species	Stratum†	Community type											
		Upland grass			Crowberry—grass—sedge			Crowberry—sedge—grass			Sedge—lichen		
		D—D‡	F	Index	D—D	F	Index	D—D	F	Index	D—D	F	Index
<i>Calamagrostis nutkaensis</i>	A	6.9	100	(690)§	5.4	100	540	3.4	81	275	3	17	34
<i>Carex macrochaeta</i>	A	6.0	88	(528)	3.7	63	233	5.0	70	350	3.5	33	116
<i>Carex lyngbyaei</i>	A	4.9	88	(431)	4.2	14	59	4.4	46	202	5.0	33	165
<i>Conioselinum chinense</i>	A	4.4	63	(277)	4	3	12	N			N		
<i>Equisetum arvense</i>	A	2.6	88	(229)	2.5	49	123	2.3	69	159	2.0	67	134
<i>Claytonia sibirica</i>	A	3.8	50	(190)	2.0	6	12	2.0	5	10	N		
<i>Polygonum viviparum</i>	A	2.8	63	(176)	2.9	23	67	4	3	12	N		
<i>Viola langsdorffii</i>	A	3.5	50	(175)	2.3	23	53	2.8	11	31	1	17	17
<i>Athyrium</i> sp.	A	5.3	38	(201)	8	3	24	5.5	5	28	N		
<i>Festuca rubra</i>	A	3.5	50	(175)	2.9	26	75	3.0	11	33	2.5	50	115
<i>Angelica lucida</i>	A	3.7	38	(141)	3.4	23	78	2.8	32	90	2.7	50	135
<i>Elymus arenarius</i>	A	7	12	(84)	N			N			N		
<i>Phleum alpinum</i>	A	2	12	(24)	3	3	9	N			N		
<i>Carex kelloggii</i>	A	4	12	(48)	2	3	6	N			N		
<i>Luzula</i> sp.	A	2.0	38	(76)	3	3	9	2	5	10	3	17	51
<i>Plantago macrocarpa</i>	A	4.0	25	(100)	2.5	11	28	2.0	5	10	4	17	68
<i>Senecio pseudo-arnica</i>	A	3	12	(36)	N			N			N		
<i>Galium trifidum</i>	A	2.7	38	(103)	2	3	6	N			N		
<i>Fritillaria camschatcensis</i>	A	4	12	(48)	N			N			N		
<i>Mnium</i> sp.	C	3.5	25	(88)	N			N			N		
<i>Carex circinnata</i>	A	3	12	36	3.2	63	(202)	3.4	57	194	3.0	50	150
<i>Agrostis</i> sp.	A	N			3.5	23	(81)	1.8	16	29	N		
<i>Platanthera dilatata</i>	A	4.0	25	100	2.3	46	(106)	3.1	19	60	2	17	34
<i>Coptis trifolia</i>	A	3	12	36	2.4	63	(151)	2.5	59	148	2.3	50	115
<i>Lycopodium</i> sp.	A	N			2.5	66	(165)	2.0	49	98	2.0	33	66
<i>Geum calthifolium</i>	A	N			3.8	26	(99)	4.7	8	38	N		
<i>Erigeron peregrinus</i>	A	3.7	38	141	3.9	43	(168)	3.8	35	133	5.0	33	165
<i>Arnica unalaschcensis</i>	A	N			4.6	29	(133)	5	3	15	N		
<i>Anemone narcissiflora</i>	A	3	12	36	3.8	11	(42)	4	3	12	N		
<i>Campanula lasiocarpa</i>	A	N			2.4	20	(48)	3	3	9	N		
<i>Tofieldia coccinea</i>	A	N			2	3	(6)	N			N		
<i>Antennaria dioica</i>	A	N			2	3	(6)	N			N		
<i>Sibbaldia procumbens</i>	A	N			2.0	6	(12)	2	3	6	N		
<i>Veronica</i> sp.	A	N			2.3	9	(21)	3	3	9	N		
<i>Lupinus nootkatensis</i>	A	N			2	3	(6)	N			N		
<i>Empetrum nigrum</i>	B	N			7.5	100	(750)	7.0	100	700	4.2	83	349
<i>Cornus suecica</i>	B	N			3.1	43	(133)	3.2	27	86	3.0	33	99
<i>Linnaea borealis</i>	B	N			3.2	57	(182)	2.7	35	95	3	17	51
<i>Loiseleuria procumbens</i>	B	N			4.6	26	(120)	2.4	32	77	N		
<i>Cassiope lycopodioides</i>	B	N			2.8	14	(39)	3	3	9	N		
<i>Salix arctica</i>	B	N			4	3	(12)	N			N		
<i>Salix cyclophylla</i>	B	N			4	3	(12)	N			N		
<i>Thamnia vermicularis</i>	C	N			2.0	69	(138)	1.6	57	91	2	17	34
<i>Dicranum</i> sp.	C	N			2.2	46	101	2.2	32	70	N		
<i>Mycoblastus</i> sp.	C	N			3.5	17	(60)	4.5	5	23	N		

(Table continues on page 214.)

Table 1—(Continued)

Species	Stratum†	Community type											
		Upland grass			Crowberry— grass—sedge			Crowberry— sedge—grass			Sedge—lichen		
		D—D‡	F	Index	D—D	F	Index	D—D	F	Index	D—D	F	Index
<i>Alectoria</i> sp.	C	N			3.0	14	(42)	N			N		
<i>Climacium dendroides</i>	C	N			3	3	(9)	N			N		
<i>Bryum</i> sp.	C	N			3.3	9	(30)	N			N		
<i>Salix rotundifolia</i>	B	N			4	3	(12)	4	3	(12)	N		
<i>Saxifraga</i> sp.	A	N			2	3	(6)	2	3	(6)	N		
<i>Ranunculus occidentalis</i>	A	N			4	3	(12)	4	3	(12)	N		
<i>Hieracium triste</i>	A	N			3	3	(9)	3	3	(9)	N		
<i>Carex</i> sp.	A	N			N			5	3	(15)	N		
<i>Achillea borealis</i>	A	2.7	38	103	2.4	46	110	2.1	62	(130)	2.3	50	115
<i>Vaccinium vitis-idaea</i>	B	N			2.1	77	162	2.7	98	(265)	2.5	83	208
<i>Cladonia pacifica</i>	C	N			5.9	94	555	7.4	97	(718)	8.6	83	714
<i>Rhacomitrium lanuginosum</i>	C	N			3.6	51	184	3.6	78	(281)	6.0	33	198
<i>Antitrichia curtipendula</i>	C	N			3.5	6	21	2.8	16	(45)	N		
<i>Ptilium crista-castrensis</i>	C	N			2.8	14	39	4.0	11	(44)	N		
<i>Hypnum</i> sp.	C	N			2	3	6	2.0	8	(16)	N		
<i>Peltigera</i> sp.	C	N			4.0	6	24	2.5	16	(40)	2	17	34
<i>Trisetum spicatum</i>	A	N			N			N			2	17	34
<i>Carex pluriflora</i>	A	4.8	50	240	2.9	23	67	3.9	46	179	3.6	83	(299)
<i>Carex anthoxantha</i>	A	4.3	38	163	1	3	3	2.7	16	43	3.0	83	(249)
<i>Eriophorum</i> sp.	A	N			N			1.5	5	8	1.3	50	(65)
<i>Juncus</i> sp.	A	4.0	25	100	3	3	9	2.8	11	31	3.0	50	(150)
<i>Rubus</i> sp.	A	2.0	38	76	3.2	49	157	3.9	59	230	3.8	67	(255)
<i>Trientalis europaea</i>	A	N			2.1	60	126	2.5	78	195	2.8	83	(232)
<i>Epilobium</i> sp.	A	2	12	24	N			2.7	8	22	1.5	33	(50)
<i>Cerastium</i> sp.	A	1.0	25	25	N			1	3	3	2	17	(34)
<i>Listera cordata</i>	A	N			1.8	17	31	1.0	5	5	3	17	(51)
<i>Chrysanthemum arcticum</i>	A	N			4.0	6	24	4	3	12	2	17	(34)
<i>Caltha palustris</i>	A	N			N			N			3.0	33	(99)
<i>Cystopteris</i> sp.	A	N			N			N			2	17	(34)
<i>Polytrichum</i> sp.	C	N			2.3	40	92	2.3	27	62	2.0	66	(132)
<i>Sphagnum</i> sp.	C	N			5	3	15	3.3	8	26	3.5	33	(116)
<i>Hylocomium splendens</i>	C	N			2.7	40	108	2.5	27	68	3.8	66	(251)
<i>Rhytidiadelphus loreus</i>	C	3.0	50	150	2.8	51	143	2.4	27	65	2.8	83	(232)
<i>Plagiothecium undulatum</i>	C	N			2	3	6	N			2	17	(34)

*Indexes were calculated by multiplying the average Domin—Dahl (D—D) abundance—coverage values for each species by the percent frequency of occurrence (F) in the community type. Eighty-six 1-m² quadrats were taken, 8 in upland grass, 37 in crowberry—grass—sedge, 35 in crowberry—sedge—grass, and 6 in sedge—lichen communities. The calculation of indexes allows the samples to be compared regardless of the number of plots. The tabulation proceeds from relatively dry to relatively wet communities.

†Strata (synusiae) used for convenience denote: A, grasses, sedges, herbs, and ferns; B, subshrubs; and C, mosses, lichens, and liverworts. Complete species nomenclature is given in Table 2.

‡Domin—Dahl values averaged in this table:

- 1 Occurring as one or two individuals with normal vigor; no measurable cover.
- 2 Occurring as several individuals; no measurable cover.
- 3 Occurring as numerous individuals but with cover less than 4% of total area.
- 4 Cover up to one-tenth (4 to 10%) of total area.
- 5 Cover up to one-fourth (11 to 25%) of total area.
- 6 Cover one-fourth to one-third (26 to 33%) of total area.
- 7 Cover one-third to one-half (34 to 50%) of total area.
- 8 Cover one-half to three-fourths (51 to 75%) of total area.
- 9 Cover three-fourths to nine-tenths (76 to 90%) of total area.
- 10 Cover nine-tenths to complete (91 to 100%).

N indicates no occurrence.

§Number in parentheses is the highest index for each species.

Table 2—Plants of Amchitka†

MOSESSES

Aulacomnium palustre (Hedw.) Schwaegr.
Bryum sp.
Climacium dendroides (Hedw.) Web & Mohr.
Fontinalis neomexicana
Dicranum sp.
Hylocomium splendens (Hedw.) B.S.G.
Hypnum sp.
Mnium sp.
Plagiothecium undulatum (Hedw.) B.S.G.
Polytrichum sp.
Ptilium crista-castrensis (Hedw.) Brid.
Rhacomitrium lanuginosum (Hedw.) Brid.
Rhytidadelphus loreus (Hedw.) Warnst.
Sphagnum sp.

LICHENS

Alectoria sp.
Cladonia pacifica Ahti
Cladonia sp.
Mycoblastus sp.
Peltigera sp.
Thamnolia vermicularis (Sw.) Ach. ex Schaer.

VASCULAR PLANTS

Boraginaceae

**Mertensia maritima* ssp. *asiatica* Takeda
 ***Mertensia maritima* ssp. *maritima* Hult.

Callitricheae

**Callitriche anceps* Fern.
 **Callitriche hermaphroditica* L.

Campanulaceae

**Campanula chamissonis* Federov
 **Campanula lasiocarpa* ssp. *lasiocarpa* Hult.

Caprifoliaceae

**Linnaea borealis* ssp. *borealis* Hult.

Caryophyllaceae

**Cerastium aleuticum* Hult.
Cerastium beeringianum var. *beeringianum* Hult.
Cerastium fischerianum Ser.
 **Cerastium fontanum* ssp. *triviale* (Link) Jalas.
 **Honckenya peploides* ssp. *major* (Hook.) Hult.
 **Sagina crassicaulis* S. Wats.
 **Sagina intermedia* Fenzl.
 **Sagina occidentalis* S. Wats.
Stellaria calycantha ssp. *calycantha* Hult.
Stellaria media (L.) Vill.
 **Stellaria ruscifolia* ssp. *aleutica* Hult.
 **Stellaria sitchana* var. *bongardiana* (Fern.) Hult.

Compositae

**Achillea borealis* Bong.
 **Anaphalis margaritacea* (L.) Benth. & Hook.
 **Antennaria dioica* (L.) Gaertn.
Antennaria pallida E. Nels.

Compositae (continued)

**Arnica unalaschcensis* Less.
 **Chrysanthemum arcticum* ssp. *arcticum* Hult.
 **Erigeron peregrinus* ssp. *peregrinus* Hult.
Hieracium gracile var. *alaskanum* Zahn.
 **Hieracium triste* Willd.
 **Petasites frigidus* (L.) Franch.
 **Senecio pseudo-arnica* Less.
 **Taraxacum trigonolobum* Dahlstedt

Cornaceae

Cornus canadensis L. x *suecica* L.
 **Cornus suecica* L.

Cruciferae

Aphragmus eschscholtzianus Andr.
 **Cardamine bellidifolia* L.
 **Cardamine unbellata* Greene
 **Cochlearia officinalis* ssp. *oblongifolia* (DC.) Hult.
 **Draba aleutica* Ekman
 **Draba hyperborea* (L.) Desv.
 **Subularia aquatica* L.

Cyperaceae

**Carex anthoxantha* Presl.
 **Carex bigelowii* Torr.
 **Carex circinnata* C. A. Mey.
Carex dioica ssp. *gynocrates* (Wormsk.) Hult.
 **Carex kelloggii* W. Boott
 **Carex lyngbyaei* Hornem.
 **Carex macrochaeta* C. A. Mey.
Carex nesophila Holm.
 **Carex pluriflora* Hult.
Carex saxatilis ssp. *laxa* (Trautv.) Kalela
 **Carex stylosa* C. A. Mey.
 ***Eriophorum angustifolium* Honck.
 **Eriophorum russeolum* ssp. *rufescens* (Anders.) Hyl.
 **Eriophorum russeolum* var. *majus* Sommier
Trichophorum caespitosum (L.) Hartm.

Diapensiaceae

Diapensia lapponica ssp. *obovata* (F. Schm.) Hult.

Empetraceae

**Empetrum nigrum* ssp. *nigrum* Hult.

Equisetaceae

**Equisetum arvense* L.

Ericaceae

**Cassiope lycopodioides* (Pall.) D. Don.
 **Loiseleuria procumbens* (L.) Desv.
 **Rhododendron camtschaticum* ssp. *camtschaticum* Hult.
 **Vaccinium uliginosum* ssp. *microphyllum* Lange
 **Vaccinium vitis-idaea* ssp. *minus* (Lodd.) Hult.

Gentianaceae

**Gentiana amarella* ssp. *acuta* var. *plebeja* (Cham. & Schlecht.) Hult.
 **Gentiana aleutica* Cham. & Schlecht.

(Table continues on page 216.)

Table 2—(Continued)

Geraniaceae

- **Geranium erianthum* DC.

Gramineae

- **Agrostis alaskana* Hult.
 **Agrostis borealis* Hartm.
Agrostis exarata Trin.
 **Alopecurus aequalis* Sobol.
 **Bromus sitchensis* var. *aleutensis* (Trin.) Hult.
 ***Calamagrostis canadensis* ssp. *langsdoerffii* (Link) Hult.
 **Calamagrostis nuthkaensis* (Presl) Steud.
Deschampsia alpina (L.) Roem. & Schult.
 **Deschampsia beringensis* Hult.
 **Deschampsia caespitosa* ssp. *orientalis* Hult.
 **Elymus arenarius* ssp. *mollis* var. *mollis* Hult.
 **Festuca brachyphylla* Schult.
 **Festuca rubra* L.
 **Festuca rubra* ssp. *aucta* (Krecz. & Bobr.) Hult.
Hierochloë odorata (L.) Wahlenb.
 ***Hordeum brachyantherum* Nevski.
 **Phleum commutatum* var. *americanum* (Fourn.) Hult.
 **Poa alpina* L.
Poa arctica ssp. *williamsii* (Nash) Hult.
 **Poa eminens* Presl.
Poa hispidula var. *aleutica* Hult.
Poa hispidula var. *vivipara* Hult.
Poa malacantha Kom.
Poa lanata Scribn. & Merr.
 **Poa lanata* var. *vivipara* Hult.
Poa turneri Scribn.
 **Puccinellia langeana* ssp. *alaskana* (Scribn. & Merr.) Sørensen.
 **Trisetum spicatum* ssp. *alaskanum* (Nash) Hult.
 **Vahlodea atropurpurea* ssp. *latifolia* (Hook.) Pors.
 **Vahlodea atropurpurea* ssp. *paramushirensis* (Kudo) Hult.

Haloragaceae

- Hippuris montana* Ledeb.
 **Hippuris vulgaris* L.
 **Myriophyllum spicatum* L.

Iridaceae

- **Iris setosa* ssp. *setosa* Hult.

Isoëtaceae

- **Isoetes muricata* ssp. *maritima* (Underw.) Hult.

Juncaceae

- **Juncus arcticus* ssp. *sitchensis* Engelm.
 **Juncus biglumis* L.
 **Juncus ensifolius* Wikstr.
 **Juncus triglumis* ssp. *albescens* (Lange) Hult.
 **Luzula arcuata* ssp. *unalaschensis* (Buchenau) Hult.
Luzula multiflora ssp. *kobayasii* (Satake) Hult.
 **Luzula multiflora* ssp. *multiflora* var. *frigida* (Buchenau) Sam.
Luzula parviflora ssp. *parviflora* Hult.
 **Luzula tundricola* Gorodk.
Luzula wahlenbergii ssp. *piperi* (Cov.) Hult.

Leguminosae

- **Lathyrus maritimus* ssp. *pubescens* (Hartm.) C. Regel
Lathyrus palustris ssp. *pilosus* (Cham.) Hult.
 **Lupinus nootkatensis* Donn
 **Trifolium repens* L.

Lentibulariaceae

- **Pinguicula vulgaris* ssp. *macroceras* (Link) Calder & Taylor

Liliaceae

- **Fritillaria camschatcensis* (L.) Ker-Gawl.
 **Majanthemum dilatatum* (How.) Nels. & Macbr.
 **Streptopus amplexifolius* (L.) DC.
 **Tofieldia coccinea* Richards

Lycopodiaceae

- **Lycopodium alpinum* L.
 **Lycopodium annotinum* ssp. *annotinum* Hult.
 **Lycopodium clavatum* ssp. *clavatum* Hult.
 **Lycopodium sabinaefolium* var. *sitchense* (Rupr.) Fern.
 **Lycopodium selago* ssp. *selago* Hult.

Onagraceae

- Epilobium behringianum* Haussk.
 **Epilobium glandulosum* Lehm.
 **Epilobium sertulatum* Haussk.

Orchidaceae

- **Dactylorhiza aristata* (Fisch.) Soó.
 **Listera cordata* var. *nephrophylla* (Rydb.) Hult.
 **Platanthera chorisiana* (Cham.) Rchb.
 **Platanthera convallariaefolia* (Fisch.) Lindl.
 **Platanthera dilatata* (Pursh) Lindl.
 **Platanthera tipuloides* var. *behringiana* (Rydb.) Hult.

Papaveraceae

- **Papaver alaskanum* Hult.

Pinaceae

- **Picea sitchensis* (Bong.) Carr. (planted)

Plantaginaceae

- **Plantago macrocarpa* Cham. & Schlecht.
 **Plantago maritima* ssp. *juncoides* (Lam.) Hult.

Polygonaceae

- **Koenigia islandica* L.
Oxyria digyna (L.) Hill
 **Polygonum viviparum* L.
 **Rumex fenestratus* Greene
Rumex obtusifolius L.

Polypodiaceae

- **Athyrium felix-femina* ssp. *cyclosorum* (Rupr.) Christens.
 ***Botrychium lunaria* (L.) Sw.
 **Cystopteris fragilis* ssp. *fragilis* Hult.
 **Dryopteris dilatata* ssp. *americana* (Fisch.) Hult.
 **Gymnocarpium dryopteris* (L.) Newm.

Table 2—(Continued)

Polypodiaceae (continued)

- **Polypodium vulgare* ssp. *occidentale* (Hook.) Hult.
- Thelypteris limbosperma* (All.) Fuchs
- **Thelypteris phegopteris* (L.) Slosson

Portulacaceae

- **Claytonia arctica* Adams
- **Claytonia sibirica* L.
- **Montia fontana* ssp. *fontana* Hult.

Potamogetonaceae

- ***Potamogeton vaginatus* Turcz.

Primulaceae

- **Primula cuneifolia* ssp. *saxifragifolia* (Lehm.) Sm. & Forrest
- **Trientalis europaea* ssp. *arctica* (Fisch.) Hult.

Pyrolaceae

- **Pyrola asarifolia* var. *purpurea* (Bunge) Fern.
- **Pyrola minor* L.

Ranunculaceae

- **Anemone narcissiflora* ssp. *villosissima* (DC.) Hult.
- **Caltha palustris* ssp. *asarifolia* (DC.) Hult.
- **Coptis trifolia* (L.) Salisb.
- **Ranunculus hyperboreus* ssp. *hyperboreus* Hult.
- **Ranunculus occidentalis* ssp. *insularis* Hult.
- **Ranunculus occidentalis* ssp. *nelsoni* (DC.) Hult.
- **Ranunculus reptans* L.
- **Ranunculus trichophyllus* var. *trichophyllus* Hult.

Rosaceae

- **Geum calthifolium* Menzies.
- **Geum macrophyllum* ssp. *macrophyllum* Hult.
- **Geum pentapetalum* (L.) Makino
- **Potentilla hyparctica* Malte.
- Potentilla egedii* ssp. *grandis* (Torr. & Gray) Hult.
- **Potentilla villosa* Pall.
- **Rubus chamaemorus* L.
- **Rubus arcticus* ssp. *stellatus* (Sm.) Boiv. emend. Hult.
- **Sibbaldia procumbens* L.

Rubiaceae

- **Galium aparinc* L.
- **Galium trifidum* ssp. *columbianum* (Rydb.) Hult.

Salicaceae

- **Salix arctica* ssp. *crassijulis* (Trautv.) Skvortz.
- **Salix cyclophylla* Rydb.
- Salix polaris* ssp. *pseudopolaris* (Flod.) Hult.
- **Salix rotundifolia* Trautv.

Saxifragaceae

- **Leptarrhena pyrolifolia* (D. Don) Ser.
- **Parnassia kotzebuei* Cham. & Schlecht.
- **Saxifraga bracteata* D. Don.
- Saxifraga foliolosa* var. *foliolosa* Hult.
- Saxifraga hirculus* L.
- **Saxifraga punctata* ssp. *insularis* Hult.

Scrophulariaceae

- **Castilleja unalaschcensis* (Cham. & Schlecht.) Malte
- ***Euphrasia mollis* (Ledeb.) Wettst.
- **Limosella aquatica* L.
- **Mimulus guttatus* DC.
- **Pedicularis chamissonis* Stev.
- **Rhinanthus minor* ssp. *borealis* (Sterneck) Löve
- **Veronica americana* Schwein.
- Veronica grandiflora* Gaertn.
- Veronica serpyllifolia* ssp. *humifusa* (Dickson) Syme.
- Veronica stelleri*, Pall.

Selaginellaceae

- **Selaginella selaginoides* (L.) Link

Sparganiaceae

- **Sparganium hyperboreum* Laest.

Umbelliferae

- **Angelica lucida* L.
- **Conioselinum chinense* (L.) BSP.
- **Heracleum lanatum* Michx.
- **Ligusticum scoticum* ssp. *hultenii* (Fern.) Calder & Taylor

Urticaceae

- ***Urtica lyallii* S. Wats.

Violaceae

- **Viola langsдорffii* Fisch.

†The vascular plants are those listed in Shacklette et al. (1969) plus eight species not previously recorded from the island. The mosses and lichens are those identified in sample plots. For further treatment of the cryptophytes, see Shacklette et al. (1969). *indicates specimen in The University of Tennessee Herbarium (Tenn). ** indicates new record.

Table 3—Aboveground Herbaceous and Graminoid Biomass Harvested in 1968, 1971, and 1972 at the End of the Growing Seasons (All Weights Are Constant-Air Dry)

Vegetation units*	No. plots	Average yield, g/m ²	SD†	CV, † %	Kg ha ⁻¹ year ⁻¹	Lb acre ⁻¹ year ⁻¹	Approximate area on island, km ²
Wet tundra (2)	3	31	8	26	310	277	26
Meadow (3)	8	41	18	44	410	366	154
Graminoid (4)							
Riparian	3	104	36	35	1040	928	8
Slope	3	65	21	32	650	580	
Flush	3	523	20	4	5230	4666	
Recovery (5)	4	130	66	51	1300	1160	15

*Numerals in parentheses indicate vegetation units as mapped, see Fig. 1.

†SD, relative standard deviation; CV, coefficient of variation.

Fig. 13—Idealized toposequence showing relative positions of major soil groups of Amchitka and corresponding vegetation community distribution. (Not to scale: vertical exaggeration about 5 to 1.)

shifts discernible. One of the six multipoint stations (grid) showed peat movement as the result of the Cannikin ground shock. The peat was fractured to mineral soil and moved downslope.

Two of the six point stations (lines) showed regular ordinary downslope peat movement. Measurements of total movement were only relative, but movements downslope (often over 1 cm/year) were noted. In the short period of the study at these stations (4 years), no plant-community shifts were detected, but greater peat accumulations at lower slope transitions can be at least partly explained by such movement. In addition, downslope movement results in lobes of peat that hang over the sea-cliff tops in many locations. These lobes regularly calve away into the sea or onto the beaches where they are eventually washed away (Fig. 12).

Primary Consumers

In the description of the dynamics of the terrestrial ecosystem, little was known, or could be found in the literature, about the impact of grazing by rats on what essentially is a meadow ecosystem. The Norway rat, *Rattus norvegicus* L., is the only terrestrial mammal now a member of the island biota. These animals remain in many areas of the island even in the absence of human wastes that might provide a food source.

Sampling of inland areas populated by rats revealed that grazing rats prefer the more succulent plants, particularly orchids of the genus *Platanthera*. Eighty-two rats were killed, measured, weighed, sexed, and their stomach contents examined. In 50% of the rats collected, fresh plant material comprised over one-half the stomach contents; over 20% had stomach contents consisting of more than 90% plant material by volume.

Rats were collected in areas not now frequented by man as well as in the vicinity of the main camp. The data showed that the rats are opportunistic feeders, eating anything suitable that they come upon. No evidence of systematic foraging could be found, and, with very local exceptions, the impact of rat grazing on plants was insignificant.

Primary consumption by insects was almost undetectable (Amundsen, 1974). Williamson, Emison, and White (1972) reported that several species of birds were important primary consumers of terrestrial and aquatic vascular plants, but no obvious evidence of plant consumption by grazing birds was discovered in inland areas covered in this study.

Miscellaneous Observations

Microclimate. Standard climatological data were recorded at the island airport control tower

and at other stations. These data are discussed by Armstrong (Chap. 4, this volume). Since no vegetation on the island attains the height of a standard meteorological shelter, an unofficial station with a U-tube maximum–minimum thermometer and a recording thermograph was established and maintained during three spring–fall periods. The sensors were at a height of 0.3 m above the substrate in a typical crowberry–grass–sedge meadow community located at an elevation of 40 m above sea level. The data obtained are too discontinuous for detailed analyses, but a high of 65°F and a low of 11°F were recorded, approximating the extreme temperatures recorded during the 1943 to 1948 period on which the climatological summaries of Armstrong (Chap. 4, this volume) are based. The most interesting data collected, however, show the relatively low number of consecutive days during which frost did not occur (32°F or below) to be less than 75 (3-year average) consecutive frost-free or growing season days at this station. These rather short periods emphasize one measured characteristic of the maritime tundra microclimate, the large number of days before and after the growing season period during which daily freeze–thaw occurs. Standard data indicate a limited daily temperature range, and the 0.3-m station records show that there are long periods in the spring and fall when frost occurs at night and thaw takes place during the day. Although damage to well-established vegetation could not be detected as a result of this freeze–thaw phenomenon, individual frost-heaved plants are conspicuous on disturbed mineral substrates. The effect is to retard the recovery of disturbed substrates by plant colonization.

Solar-Energy Input. A pyranometer was in operation at the airport control tower over much of the time during 1969 to 1971, but there are uncertainties about the accuracy of the data collected (Armstrong, Chap. 4, this volume). Subjective observations during the growing seasons of 1969 and 1970 indicated rather low solar-energy input, and therefore in 1971 informal backup measurements of incident solar energy were made, also atop the control tower. Three Saint Paul Scientific SPS-10-30 solar integrating meters were used. The average daily total was calculated at 260 langleys for the 3-month summer period. This compares favorably with the 1969 to 1971 pyranometer data presented in Chap. 4. A daily average of 260 langleys incident on the Amchitka recorders indicates a 50 to 75% reduction of solar radiation expected at the Amchitka latitude for June–July–August. This means that the Amchitka climate is one of the world's cloudiest, at least during the growing season.

Wildfire. On two occasions in 1968, fire of unknown origin (probably man-caused) carried over crowberry meadow communities consuming standing dead and some living vegetation. One fire covered about 40 acres (about 16 ha), but the other was considerably smaller. In both cases, except for the incineration of the standing dead and the charring of some aerial living plant material, the fires had no lasting effect on the vegetation and no discernible effect on the substrate or subsequent plant-community composition. Informal experiments have demonstrated that it is very difficult to ignite the Amchitka peat.

Lightning. Lightning and thunderstorm activity rarely occurs over small islands in maritime tundra ecosystems. At three different times during the course of this study, cloud–ground lightning was directly observed. Thunder was heard on a few other occasions, but thunderstorms and lightning storms appear to have little effect on this ecosystem.

Cannikin Disturbance Transects

After the Cannikin detonation in November 1971, 10 line-intercept transects were established across representative types of disturbances to adjacent stable vegetation. The transects were established soon after the event, when the pre-Cannikin status of the plant cover could still be ascertained. The original condition of the areas crossed by the transects and tendencies revealed by subsequent examinations are as follows:

1. An area of about 0.5 ha was temporarily flooded by the collapse of a road culvert. The culvert was reopened in a matter of days but in a higher position so that the water remains above pre-Cannikin levels. The substrate adjacent to the present waterline remains saturated. This small area was formerly crowberry–sedge–grass meadow on both sides of a small stream. With the present higher water table, this transect area will tend toward and probably stabilize as sedge–lichen meadow.

2. This was also a temporarily flooded area, but the culvert that collapsed was restored in the original position in a matter of days and the area was drained. Since the transect was located, the few necrotic plants that defined the area have been replaced by others, and the crowberry–grass–sedge meadow aspect has been restored.

3. This is a very shallow but permanent pond where the Cannikin shock caused an abrupt violent seiche through an old inactive drain. Although vegetation in the drain was briefly inundated 4 to 5 ft above the normal 1-ft depth of the pond, there was no discernible lasting effect.

4. This area was across a major collapse crater fracture and into the new Cannikin Lake before it filled. This was crowberry-grass-sedge meadow, but the transect is now completely under water.

5. A berm separating a construction storage area from a wet crowberry-sedge to sedge-lichen meadow was breached by the Cannikin shock, allowing petroleum and other pollutants to flow over a fan-shaped area. Over a 2-year period since the leakage, signs of plant necrosis have become much less noticeable, and the area will recover as wet meadow.

6. During the winter of 1972, packing paper was dumped and left across a crowberry-grass stripe community near the main road along the spine of the island. The paper has now (1974) nearly disappeared, and the effect (of the paper as a possible mulch) appears to have been nil.

7. A pond was temporarily drained as a result of Cannikin shock. An *Eriophorum* (cotton sedge) community showed no change as the water level gradually returned to previous levels.

8. This transect is across an area flooded from Cannikin test time (Nov. 6, 1971) to Sept. 20, 1972, when a culvert was reopened. The area flooded was crowberry-grass-sedge meadow. A year after the flooding ended, only sedges had reestablished along the transect, and they were scattered. The grasses and crowberry that were inundated remain necrotic (1974). Lateral encroachment of the adjacent meadow vegetation will lead to complete recovery in a few years.

9. Oil and drill mud were spilled on an area adjacent to a road that bore scattered crowberry-grass stripe vegetation on a mineral substrate. All visible plants were killed. There is no sign of reestablishment, and there may not be for decades.

10. Tundra flap (severe fluffing of the previously compact vegetative mat) occurred over a large area. Many small hummocks and mounds showed apical disturbance, and a large number of crowberry plants were sheared off at the soil interface. Reexamination of the transect across the area revealed that continued lateral branching of the crowberry and new root establishment have obliterated any visible effects. This area has completely recovered.

RECOVERY

A project was specifically designed and carried out to quantitatively describe and evaluate the dynamics of the vascular vegetation on disturbed areas of the island (Chilcoat, 1973; Amundsen, 1974). An attempt was made to collect information with some predictive value in assessing the revegetative potentials of similar new or antici-

pated areas of disturbance in this and similar ecosystems. The site characteristics taken into account are listed in Table 4.

Table 4—Site Classifications for Disturbance Study

Disturbance causes	Slope % units
1. Road construction cut.	1. 1 to 9
2. Building or road berm.	2. 10 to 14
3. Road surface (compacted).	3. 15 to 19
4. Road surface (filled).	4. 20 to 24
5. Building or gun emplacement floor (uncompacted).	5. 25 to 29
6. Blast crack.	6. 30 to 34
7. Ecological experiment.	7. 35 to 39
8. Frost scar.	8. 40 to 44
9. Mud flow.	9. 45 to 49
10. Filled walk.	10. 50 to 54
11. Slide area.	11. 55 to 59
12. Road shoulder (filled).	12. 60 to 64
13. Burned building floor.	13. 64 to 69
	14. 70 plus
History (time of disturbance)	
1. World War II (1943 to 1948).	
2. Long Shot (1965).	
3. Ecology experiments (1968).	
4. Milrow (1969).	
5. Other.	
Exposure	Aspect
1. Protected.	1 to 8 The octamerous
2. Moderately protected.	compass
3. Moderately exposed.	directions.
4. Exposed.	9 Flat.
5. Very exposed.	

When the field work was completed, with a total of 20,946 hit samples, the data were computer analyzed for plant distribution percentages for each plot and for each category of site characteristics, for correlations among species and among site factors and species, and by regression analysis for species relationships with site factors.

On the maritime tundra of Amchitka, classical processes of directional plant succession toward a mesophytic climax could not be demonstrated. However, with the use of correlation analyses, three assemblages of higher plant species that show strong correlations in occurrence among species could be identified. These three assemblages* (two of four species each and one of eight species) can possibly be considered as associates (the nuclei of incipient community types), but these assemblages, along with a few other statistically identifiable

*(A) *Claytonia sibirica*, *Elymus arenarius*, *Ranunculus occidentalis*, and *Athyrium* sp.; (B) *Koenigia islandica*, *Luzula tundricola*, *Polygonum viviparum*, *Saxifraga punctata*, *Veronica stelleri*, *Salix arctica*, *Salix cyclophylla*, and *Potentilla hyparctica*; (C) *Carex circinnata*, *Cassiope lycopodioides*, *Potentilla hyparctica*, and *Salix rotundifolia*.

groupings of species, could not be assigned to a definite chronological position in seral succession.

The data were also examined by regression analyses for relationships between plant taxa and site factors. As might be expected, the site factors "history" and "disturbance type" were more frequently indicated as "important" by the coefficient of determination (R^2) than any other site factors. Again, however, no directional successional sequence could be predicted from the data regardless of the cause, history, or location of the disturbed site.

These combined findings point out the lack of demonstrable secondary succession on this maritime tundra landscape and have led to the conscious choice of the word and concept of *recovery* as the most accurate description of the process that is currently occurring in the disturbed areas.

DISCUSSION AND CONCLUSIONS

Amchitka Island has a maritime tundra regime. The physical environment is characterized by

1. Narrow temperature ranges, with a maximum of 65°F and a minimum of 14°F (18°C to -10°C), were recorded over a several-year period (Armstrong, Chap. 4, this volume). Common diurnal maximums and minimums just above the vegetation are 58°F to 48°F (14.5°C to 9°C) in the summer and 35°F to 25°F (2°C to -4°C) in the winter. Nightly freeze and daily thaw are common from November through April.

2. Nearly constant wind, often of considerable velocity, without prevailing direction, as indicated by lack of vegetational orientation.

3. Evenly distributed precipitation, approximately 33 in. per year (838 mm) in gage catches with an additional 10 in. (254 mm) or so probably added by fog interception by the vegetation.

4. Heavy fog and cloudiness, particularly during the June to September growing season.

5. Low solar-energy input, approximately 74 kilolangleys/year.

6. Igneous bedrock with retarded release of nutrients in areas where peat accumulations are a mantle.

Most of the landscape supports a subarctic maritime tundra-vegetative continuum that, although there is no permafrost and little deep penetration of winter frost, in aspect and plant genera resembles better known alpine and arctic tundra. For convenience the tundra vegetation can be divided into two topoenvironmental units, lowland and upland, based on floristics, autecological and synecological responses, exposure, and soil-moisture drainage. A distinct topoenviron-

mental unit is found on the sandy beaches (and on certain coastal dunes), which are often isolated as the result of rather impressive sea cliffs. The community types and the types and type groups mapped in the topoenvironmental units are shown in Fig. 1.

Lowland Tundra

The lowland tundra terrestrial communities vary in composition and structure from the wettest expression, ephemeral pools usually dominated by *Juncus arcticus*, *Alopecurus aequalis*, or *Sparganium hyperboreum*, to the driest of the lowland communities, meadows of *Empetrum nigrum* (crowberry)—*Carex* spp.—*Calamagrostis nutkaensis*. The tundra continuum changes from lowland to upland units with a distinct shift in productivity from sedge dominance to grass dominance and a more obvious presence of crowberry. The crowberry-sedge-grass and crowberry-grass-sedge meadows together cover approximately 55% of the island.

Between the ephemeral pools and the crowberry meadow are two intermediate communities that together cover approximately 9% of the island. The first is a breakaway tundra dominated by sedges and lichens (the lichen *Cladonia pacifica* is particularly conspicuous). The breakaway tundra community type, characterized by the lack of abundant well-rooted plants, is distinguished by the ease with which the living vegetation is disturbed or literally broken away even by foot traffic. The second intermediate community is a sedge-lichen meadow that, although containing in general the same species as the breakaway tundra, also contains more grass, sedge, and some crowberry that stands up under light foot traffic but not under vehicular traffic. Quantitative vegetational samples taken in the sedge-lichen meadow indicate that *Carex pluriflora* and *Carex anthoxanthea* are characteristic of the type (see Table 1).

The semiaquatic plants *Alopecurus aequalis* and *Sparganium hyperboreum* are found only in the ephemeral pool habitats, but most of the other plants of the lowland tundra communities grow in varying densities throughout the lowland unit.

The primary factor controlling the cover and abundance of the various species of lichens, sedges, grasses, subshrubs, and herbs is the drainage characteristic in and on the often slowly moving peat substrate. As the moisture gradient changes from an area of waterlogged fen to an area of more mesic bog [an acid treeless peatland . . . relatively dry (Ahti and Hepburn, 1967)] that has some drainage (even though it may be severely retarded), the trend toward more mesomorphic plants fol-

lows. Extremely hydromorphic plants, such as *Juncus arcticus* and *Caltha palustris*, are found in abundance in the often extensive areas of nearly closed drainage and occasionally in places temporarily covered by slowly flowing shallow water.

At the drier end of the lowland tundra gradient, these plants usually occur in areas that have been disturbed and often hold standing water as a result of subsidence or compaction (such as old vehicle tracks). The more mesomorphic plants, such as crowberry and *Calamagrostis nutkaënsis*, although more abundant at the dry end of the lowland moisture gradient, grow in portions of generally very wet areas with slightly improved drainage. Low hummocks of peat (again often caused by past disturbances) support those species less tolerant of excess moisture.

Conspicuous turf mounds of complex and unresolved origin in lowland tundra support vascular plants common to the upland tundra unit. Crowberry, *Loiseleuria procumbens*, *Vaccinium vitis-idaea*, and *Calamagrostis nutkaënsis* are most often encountered on the mounds that provide the better drainage conditions preferred by the upland plants.

The substrate for the lowland tundra topoenvironmental vegetation is mostly a sedge–lichen peat, generally varying from a depth of 0.3 to 0.6 m on moderate slopes to depths in excess of 4 m on lower slope transitions. The lowland tundra is dotted with ponds and shallow lakes that are often supported by peat. Small streams are common. The terrain varies from flat to moderate slopes, and the absorbent peat over an impervious bedrock retains enough water to limit the dominant plant species to those which are relatively hydromorphic.

Upland Tundra

In the better drained upland tundra of Amchitka, the vegetation is generally dominated by grass or crowberry or a mixture of the two. The prominent grasses are *Calamagrostis nutkaënsis*, *Elymus arenarius*, and *Festuca rubra*. The upland tundra also includes several important sedge species (*Carex circinnata*, *C. lyngbyaei*, *C. macrochaeta*), and certain *Juncus* and *Luzula* species are conspicuous in some situations. *Salix* spp. and *Vaccinium* spp. are found on well-drained sites, and *Loiseleuria procumbens* is also an important member of some of the subshrub communities.

Certain sites of the island (approximately 3% of the area) support almost pure graminoid communities. These better drained sites are located at the edges of permanent lakes, along well-established streams, just above steep sea cliffs, and on

steep slopes with a relatively well-developed soil. Some of these stands cover considerable acreage and grow to nearly 1 m (3.3 ft) in stature.

The upland tundra grades from the crowberry–grass–sedge meadow to the wind-desiccated crowberry–grass stripes, which are broken by barren lag-gravel solifluction–deflation areas at higher elevations on the island. The stripe zone covers about 26% of the island. The crowberry–grass–sedge meadow type is the most stable vegetation on the island on moderately to relatively well-drained topography.

Lag-gravel surfaces at higher elevations [generally above 75 m (246 ft)] have complex origins and processes of maintenance. One possible contributing factor is the apparent pathogenicity of a lichen of the genus *Mycoblastus* on the crowberry. Once the upland vegetation has been destroyed, whether by physical forces or organic agents, an uninsulated bare gravel–soil surface subject to wind erosion and frost action results. The processes that control the establishment or reestablishment of vegetation on such exposed areas are not completely clear. Many of these surfaces have likely existed since vegetation developed on the island under the present climatic regime, but the pattern of the vegetated crowberry–grass stripes and intervening gravel surfaces is continually changing over the years. Even with the migration of the vegetation stripes and the downslope and vertical frost-heaving movement of the gravel, the overall aspect of the undisturbed portions of this landscape type is unlikely to change much given the present flora of the island.

In summary, the upland tundra vegetation grades from meadow to subshrub stands, reflected by lesser accumulations of peat as drainage improves and mineral-soil-forming processes become more pronounced. The lag gravel–soil surfaces are the driest well-represented substrates on the island except for the beaches, but, when rainfall is copious, even these soils tend to remain at field capacity.

Beach Community

The prevalent beach community, located above spring tide on beaches wide and high enough to prevent storm flooding, is dominated by grasses. The same sort of community appears on dunes, on the small islets off the coast, and on some of the larger sea stacks. The aspect dominant is *Elymus*, but *Calamagrostis*, *Festuca*, and *Poa eminens* are also common. Early in the growing season, geophytic herbs (especially *Ranunculus* spp., *Geum macrophyllum*, and certain Umbelliferae) provide a conspicuous touch of green, but, as the grasses

develop fully and the canopy closes, the vernal plants are less noticeable. The conspicuous but small *Potentilla villosa* is common in niches in rocks on the sea cliffs and stacks, often with *Mimulus guttatus*.

A rather scattered community composed mostly of decumbent succulent herbs is generally found between the grass community and the spring tidemark. Nowhere do these often storm-washed halophytes provide a very dense cover. The principal species are *Senecio pseudo-arnica*, *Mertensia maritima*, *Honckenya peploides*, and *Lathyrus maritimus*.

The soil of the beach communities, which comprise about 1.5% of the terrestrial landscape, is almost wholly mineral substrate. Very lush expressions of vegetation of the beach community occur on the seashell—bone—calcium rich middens at the sites formerly occupied by Aleuts on or near many beaches on the island. *Urtica lyallii* is also found on many of the middens.

Community Comparisons and Dynamics

Many species are well represented in more than one plant-community type. This complicates the delineation of community boundaries. Prominent among these widely distributed species are the grasses *Calamagrostis nutkaensis*, *Elymus arenarius*, and *Festuca* spp., the sedges *Carex circinnata*, *C. pluriflora*, and *C. macrochaeta*, the subshrub *Empetrum nigrum*, mosses of the genus *Racomitrium*, and several lichens of the genus *Cladonia*. Although many species are prominent in terms of aspect dominance, their annual biomass accumulations vary greatly.

The crowberry, lichens, and ubiquitous mosses are perhaps the most widely distributed elements of several communities. The biomass of the crowberry is probably the greatest of any of the island species, although annual accumulations are difficult to measure. Biomass accumulation rates in lichens are known to be low in other tundra locations (Ahti and Hepburn, 1967). The highest annual production by species on the island is contributed by the grasses *Calamagrostis nutkaensis* and *Elymus arenarius*. The individually productive sedges seldom form large dense stands as do the grasses except in special circumstances. The greatest net annual production on a unit-area basis is in the graminoid communities of the upland tundra unit and in the beach topoenvironmental unit.

The greatest higher plant biomass is found in the two meadow types (crowberry—sedge—grass and crowberry—grass—sedge), which total over 50% of the island's area. The annual production per unit

area is not the greatest in the crowberry meadows (Table 2) because neither the grass nor the sedge forms extensive closed stands in the rather thick crowberry mat. Although lower plants are abundant, their biomass is not great.

As is common in bog and fen communities, even the relatively low unit-area biomass production of these communities greatly exceeds annual decay and decomposition rates, and the system is far out of balance. One principal reason is the dearth of consumers and decomposing organisms. Primary consumers of living plant material are limited to certain species of birds, Norway rats, and certain invertebrates (nematodes, mites, slugs, insects, earthworms, etc.). The invertebrates also play a part in the decomposition of standing dead plant material and raw litter and humus. Bacterial decomposers are often inactive under the acid conditions existing in the peat substrates. Many fungi are known to be important in the decomposition of organic material under acid conditions, and actinomycetes are predominant in the Amchitka peat. Visual examination of the decomposing layers of the substrate reveals conspicuous hyphae, but mushrooms or other fungal fruiting bodies are infrequent (E. E. C. Clebsch, personal communication).

A general model of the terrestrial ecosystem of Amchitka is shown in Fig. 14. Although this model might imply a balance, the paucity of decomposing bacteria and fungi reduces the chances for any sort of sustained balance.

A minimal subaerial supply of certain necessary nutrients (from bird droppings, rat scat, insect casts, sea spray, and other sources) is available, but the system is heavily weighted toward nutrient tie-up. This imbalance has resulted in a continuing slow accumulation of plant residues and altered organic matter which has produced a rather thick layer of peat on flat to moderately sloping topography (Shacklette and Rubin, 1969).

The system is characterized by the slow slipping of the peat toward stream bottoms and sea cliffs. This flow is apparent in flow lines, crevasses, and "peat falls" or "calving" over abrupt subsurface topography. The movement of the peat proceeds slowly but nearly continually, changing drainage patterns. Many streams flowing over peat not derived from aquatic plants indicate stream migration. The peat movement has pushed the streams over, and new channels have been cut into the peat. Lobes and large blocks of peat observed in the streams also indicate that peat overrides existing channels. Earthquake shocks are thought to have greatly accelerated the peat movement on steeper topography, particularly at the higher elevations, and at the top of the sea cliffs where

1. **INPUT:** According to solar radiation data collected at Amchitka from February 1969 until December 1971, the island receives an average solar energy input of about $74 \text{ kcal cm}^{-1} \text{ year}^{-1}$. This estimate is subject to some uncertainty, as indicated by Armstrong (Chap. 4, this volume).

Subaerial nutrients include salt spray, animal feces, dissolved nutrients in rain and snow, etc. Atmospheric contributions include nitrogen fixed by soil microflora.

2. **PRIMARY PRODUCERS:** Includes cryptogams and phanerogams. Basic annual production study results from the "A" stratum are listed in Table 2.

3. **STANDING AND UNALTERED DEAD-PLANT MATERIAL:** Includes the previous year's crop as well as fresh litter.

4. **SOIL AND/OR PEAT:** Represents mineral soil as well as altered dead organic material. Soil and peat analyses have been made in a separate study (Everett, Chap. 9, this volume). The peat component of this compartment is a very large part of this ecosystem. The accumulation, water-retention capability, and slow movement of this peat nutrient sink controls much of the landscape aspect.

5. **PARASITIC FUNGI AND PATHOGENS:** Smuts and rusts have been seen on grasses. A lichen of the genus *Mycoblastus* appears pathogenic to the crowberry.

6. **PRIMARY CONSUMERS:** Analyses of the contents of bird crops and stomachs indicate the

consumption of fruits and some leaves of many species. Rats were found to graze on some plants. Invertebrates eat living as well as dead plant material. Sampling indicates that springtails and other insects, mites, and nematodes are present in the vegetation and in the litter at all times of the year.

7. **SECONDARY CONSUMERS:** The predation of falcons and rats is probably of only slight importance. Eagles have been seen attempting to take rats. Freshwater fish take a good number of invertebrates. Certain invertebrates, such as spiders, prey heavily on other invertebrates.

8. **SOIL MICROFLORA:** Although bacteria do not normally flourish in acid peat, nitrogen-fixing bacteria are associated with the native lupine, and visual evidence indicates the presence of both sulfur- and iron-reducing bacteria. Fungal hyphae are present in the organic horizons, but fruiting bodies are found infrequently. Preliminary tests indicate that actinomycetes are predominant.

9. **SOIL FAUNA:** Soil invertebrates are present at all seasons of the year, even in frozen litter.

10. **RESPIRATION:** This compartment is included to indicate that gross as well as net productivity should be considered.

11. **OUTPUT:** Included are hydric solution of peat, run-off that carries suspended organic and mineral matter, mineral weathering, blowout, and the calving of peat. Radiation and evapotranspiration energy losses are also included.

Fig. 14—A general qualitative model of the terrestrial ecosystem of Amchitka.

large slide and slump scars are conspicuous. The slow peat movement, with resultant crevasses, ridges, and over-cliff calving, leads to slowly changing drainage patterns and, in turn, to either improved drainage or swamping; local instability is the rule. The overall vegetation of Amchitka appears to be changing little with time but noticeably in space.

Vegetation Recovery on Disturbed Areas

Our studies have shown that secondary plant succession on Amchitka does not follow normal temperate-region patterns. Temperate climates usually allow or provide for directional secondary succession, proceeding through recognized seral stages, culminating in stable climatically adapted community types. The recently completed study at Amchitka shows that directional succession can be demonstrated only in certain parts of the mountainous terrain of Amchitka and then only rarely. Many factors control vegetation recovery (as distinct from classical secondary succession) on disturbed areas on the island. Among the factors that contribute to the generally slow rate of recovery are the depauperate flora, frost action (on mineral soils), low availability of seeds or other propagules, and the lack of weedy pioneering species.

Frost heaving limits the reestablishment of vegetation on disturbed areas of mineral soil, particularly those with fine texture. The freezing of these soils frequently produces needle-ice pedestals that lift and uproot newly established plants. Subsequent melting of the ice-soil pedestals drops the uprooted plant onto the surface where it becomes desiccated or removed by wind. On disturbed organic soils, frost heaving is essentially absent owing to the large amount of free space and to the strength of the organic fibers. However, desiccation of the organic surface either by evaporation or by freezing may destroy some new plants. Many disturbed areas recover only as the adjacent closed vegetation mat invades and covers the area.

Perhaps the controlling factor in revegetation, particularly on those sites with an organic substrate, is the low availability of a seed or propagule source. For this reason plant establishment or revegetation most often mirrors the surrounding vegetation. Recovery on most organic substrates can be expected to be substantial in 15 to 20 years. Exceptions to this generalization are produced by site alterations involving major shifts in internal drainage, in decomposition rates of the organic matter, and, occasionally, in slope aspect or exposure. Under these exceptional conditions, establishment or recovery in the area may take a course toward a plant cover quite different from that

immediately surrounding the area, and, because a seed or propagule source of a species suited to the changed environment may be at some considerable distance, the process of revegetation may take substantially longer than 20 years.

Another major reason for the lack of directional secondary succession at Amchitka is the lack of weedy taxa, which in other locations usually act quickly to alter the microclimate sufficiently to permit the orderly and sequential reestablishment of vegetation culminating in a very stable community (here the crowberry-graminoid meadow). Thus, in the classical sense, changes following disturbance in this community are better termed "recovery" than "succession."

Vegetation of the secondary-recovery type covers about 5% of the island, most of it near the eastern end. Exposed soil on berms as well as on other areas that were disturbed by road and building construction during the 1940s, often well drained because they are artificially elevated, supports the graminoid species as well as crowberry. The recovery toward an expression of the upland tundra supports the "most stable" ranking of the crowberry-grass-sedge meadow community.

Recovery of upland tundra vegetation is also slowly occurring on mixed gravel-soil surfaces of the island. Such surfaces are generally either abandoned military roads and building sites or lag-gravel surfaces resulting from natural forces in the crowberry-grass stripe deflation and solifluction zones on exposed hills and ridges. *Lupinus nootkatensis* is sometimes a pioneer in both cases. This perennial herb with its perennating bud close to the ground surface can provide both aestival shelter and nitrogen-enriched soil for the establishment of crowberry, grasses, and other herbs. Secondary recovery on gravel roads at low elevations presents few problems of interpretation. Recovery usually occurs through the spreading of adjacent plants.

Rates of Vegetation Recovery

From an examination of recovery processes on past disturbances, one can establish a loose time-frame prediction base. World War II damaged areas, such as road berms, originally of mixed organic and mineral substrates, show nearly complete recovery on the side away from the road and on the top, but, on the roadside slope of the berms, recovery on the mostly mineral substrate is inconsistent, perhaps owing to greater exposure to wind scouring and abrasion. The more gentle the slope, the better the recovery. The prominent isolated "pioneer" plants on the roadside slopes and in the road ditches are *Lupinus nootkatensis* and *Sib-*

baldia procumbens. Although these plants are conspicuous, they are seldom important in terms of coverage.

Organic substrates exposed by military activities on Amchitka during World War II show nearly complete vegetative reestablishment in almost all circumstances. In contrast, mineral substrates stripped of vegetation during World War II and since have a very spotty vegetative cover and with rare exceptions do not approach closure. It will probably be centuries, given the present climate, before these surfaces are completely vegetated.

Organic and mineral substrates disturbed in connection with the Long Shot test (1965) still show differences in recovery. Organic soils support lush stands of graminoid plants, and mineral soils still show no substantial recovery.

Milrow-period (1966 to 1969) disturbances show well-advanced recovery of graminoid species where the substrate is wholly organic. Exposures of mineral substrate from the Milrow period do not show any permanent recovery. No substrates newly exposed during the Cannikin period show permanent recovery yet except where certain beach plants have become established on fallen sea-cliff materials and previously rooted plants have grown up through shallow new mineral or organic overburdens.

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Avifaunal Investigations

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Bird populations on and near Amchitka, Alaska, were studied between 1967 and 1973 to determine species composition, ecological distribution, density, productivity, and seasonal movements. Since 1955, 131 species have been recorded there, and evidence of breeding was obtained for 28 of these. Fourteen ecological formations, based on characteristics of vegetation and physical features of the environment, were used to analyze the distribution of birds. Various species or groups of birds were studied to determine population densities and, in some cases, food habits. Marine littoral waters, sea beaches, Empetrum-Cladonia tundra, pelagic waters, and lacustrine waters, in that order, showed the greatest use by birds, and any one of these was used by nearly twice as many species as any one of the other nine formations. The Lapland Longspur had the

greatest density of the breeding birds, about one pair per acre in riparian meadow habitat, and made up over one-half of all breeding birds. Waterfowl were conspicuous elements of the avifauna, but, although there are more than 2500 lakes on Amchitka, less than 1% were used by fall and winter flocks. The perimeter of the island was used rather uniformly by breeding Bald Eagles and Peregrine Falcons, whereas cormorant colonies were less uniformly distributed. Many species were resident, but most spring migrants arrived rather suddenly. The onset of nesting was delayed in some species, although considerable synchrony was manifest in most breeding phenologies. The prime species affinity was holarctic, and the dearth of passerines reflected the disharmonic (biologically unbalanced) nature of the avifauna characteristic of many islands.

The primary objective of this investigation of birds on and around Amchitka Island was to accumulate data on the adaptations of bird life on a subarctic tundra island and to provide data necessary for the decision making of how man might use the island with minimal impact on the avifauna. Especially considered was the distribution of birds, both geographical and ecological, including spacing and numbers of individuals supported by the various plant formations typical of the area. An effort was made not only to census the birds but also to find their nests and to gather data on the reproductive success of as many species as possible. Some of these data have already been presented elsewhere (Williamson and Emison, 1969; 1971; White, Emison, and Williamson, 1971). Although not emphasized here, attention was also focused on adjustments in the annual breeding and molt

sequences that are necessary, particularly in the passerine birds, if these processes are to be completed within the short span of the northern summer and on food habits of the species on the island.

Field work was conducted between August 1967 and September 1973, and personnel were on the island every month of the year, although the least amount of time was spent there during the winter, December to February.

This investigation was devoted to collecting information on species composition, ecological distribution, density, productivity, and seasonal movements. The data gathered also pertain to a broad range of related subjects, including the faunal relationships of the birds of the region, food availability and its relation to breeding biology, and many others. This chapter contains a general review of some of the major findings relating to communities, population densities, and geographical and ecological affinities of the avifauna. We have not attempted to present all the data collected.

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SPECIES COMPOSITION

A total of 131 species have been recorded on Amchitka (Table 1), although only 124 were seen during this study. Of these, 60 occur regularly on or near Amchitka. The other seven species were recorded either by Kenyon (1961) or Lensink (1965) or collected by John McCann (reviewed by Jones and Gibson, 1975). Several species are known only from single observations or single specimens collected, and their occurrence on Amchitka must be considered as accidental. See the article by Murie (1959) for a review of species compositions of the avifauna of the Aleutians in general.

DISTRIBUTION OF POPULATIONS BY SEASON AND ECOLOGICAL FORMATION

For an analysis of the distribution of birds, certain ecological formations were recognized on the basis of vegetational cover or other distinctive environmental features. This was a necessary first step in determining those environmental parameters, including trophic positions and interrelationships, which permit any given avian species to exist on Amchitka Island. Fourteen ecological formations were identified as follows:

Pelagic waters	Alpine tundra
Marine littoral waters	Riparian meadow
Lacustrine waters	Beach ridges
Fluviatile waters	Coastal reefs
<i>Carex</i> meadow tundra	Sea beaches
<i>Empetrum</i> — <i>Cladonia</i> tundra	Sea cliffs
Disturbed areas	Offshore islands

In addition to the above ecological formations, the refuse dump attracted certain birds, and one species had a special affinity, in addition to other areas, to the dump. Figure 1 is a schematic ecological profile of Amchitka, indicating the relative positions and relationships of these formations. The ecological formations are briefly described below, and the four terrestrial formations containing census plots (*Empetrum*—*Cladonia* tundra, *Carex* meadow tundra, riparian meadow, and beach ridges) will be described in more detail later.

Pelagic Waters

The pelagic waters comprise the marine waters extending seaward beyond about 1.5 miles (2.4 km) from land.

Marine Littoral Waters

The marine littoral waters include the marine waters bordering the shore and extending about 3 km (2 miles) from land to where they merge with pelagic waters. These waters are frequently characterized by beds of kelp and an intertidal shelf extending some distance out from shore around much of the coastline.

Lacustrine Waters

All bodies of standing water and their associated emergent vegetation except the smallest ponds of the tundra formation are included in this formation.

Fluviatile Waters

All flowing surface waters are considered part of this formation. These waters include the many small streams of the island together with their margins that may be of sand, gravel, or mud. The sand, gravel, and mud are usually devoid of vegetation. No species of birds showed a primary preference for this formation during the period of study, although the Wandering Tattler occurs there regularly.

Carex Meadow Tundra

This widespread meadow-like formation is generally moist to wet underfoot and supports lush stands of *Carex* with associated herbaceous vegetation. The mosses *Sphagnum* and *Hylacomium* are common.

Empetrum—*Cladonia* Tundra

The low vegetation of this tundra is drier underfoot than that of the *Carex* meadow tundra and occupies the better drained upland sites. Characteristic plants include *Empetrum nigrum*, *Cladonia pacifica*, *Loiseleuria procumbens*, and herbaceous plants, among which *Carex*, *Cornus*, *Pedicularis*, and *Erigeron* are prominent.

Alpine Tundra

The alpine tundra formation, in the higher windswept areas of the western half of the island, consists both of bare expanses largely devoid of vegetation and of mosaics of vegetated and bare areas. Characteristic plants include *Salix* (low prostrate willows), *Vaccinium*, *Loiseleuria*, and *Empetrum*. Rocky scree is common here.

Riparian Meadow

The riparian meadow includes the dense lush stands of herbaceous vegetation bordering many

Table 1—List of Birds on Amchitka Island

<i>Gavia immer</i> : Common Loon	<i>Heteroscelus incanus</i> : Wandering Tattler
<i>Gavia arctica</i> : Arctic Loon	<i>Heteroscelus brevipes</i> : Polynesian Tattler
<i>Gavia stellata</i> : Red-throated Loon	<i>Tringa flavipes</i> : Lesser Yellowlegs
<i>Podiceps auritus</i> : Horned Grebe	<i>Calidris ptilocnemis</i> : Rock Sandpiper
* <i>Diomedea albatrus</i> : Short-tailed Albatross	<i>Calidris acuminata</i> : Sharp-tailed Sandpiper
<i>Diomedea immutabilis</i> : Laysan Albatross	<i>Calidris melanotos</i> : Pectoral Sandpiper
<i>Diomedea nigripes</i> : Black-footed Albatross	<i>Calidris bairdii</i> : Baird's Sandpiper
<i>Fulmarus glacialis</i> : Northern Fulmar	<i>Calidris minutilla</i> : Least Sandpiper
<i>Puffinus tenuirostris</i> : Short-tailed Shearwater	<i>Calidris subminuta</i> : Long-toed Stint
<i>Pterodroma inexpectata</i> : Scaled Petrel	<i>Calidris alba</i> : Sanderling
<i>Oceanodroma furcata</i> : Fork-tailed Storm Petrel	<i>Calidris alpina</i> : Dunlin
<i>Oceanodroma leucorhoa</i> : Leach's Storm Petrel	<i>Philomachus pugnax</i> : Ruff
<i>Phalacrocorax auritus</i> : Double-crested Cormorant	<i>Limosa lapponica</i> : Bar-tailed Godwit
<i>Phalacrocorax pelagicus</i> : Pelagic Cormorant	* <i>Limosa limosa</i> : Black-tailed Godwit
<i>Phalacrocorax urile</i> : Red-faced Cormorant	<i>Phalaropus fulicarius</i> : Red Phalarope
<i>Olor cygnus</i> : Whooper Swan	<i>Lobipes lobatus</i> : Northern Phalarope
<i>Branta canadensis</i> : Canada Goose	<i>Stercorarius pomarinus</i> : Pomarine Jaeger
<i>Branta bernicla</i> : Black Brant	<i>Stercorarius parasiticus</i> : Parasitic Jaeger
<i>Philacte canagica</i> : Emperor Goose	<i>Stercorarius longicaudus</i> : Long-tailed Jaeger
<i>Anser fabalis</i> : Bean Goose	<i>Larus hyperboreus</i> : Glaucous Gull
<i>Anas platyrhynchos</i> : Mallard	<i>Larus glaucescens</i> : Glaucous-winged Gull
<i>Anas strepera</i> : Gadwall	<i>Larus ridibundus</i> : Black-headed Gull
<i>Anas acuta</i> : Pintail	<i>Rissa tridactyla</i> : Black-legged Kittiwake
<i>Anas falcata</i> : Falcated Teal	<i>Rissa brevirostris</i> : Red-legged Kittiwake
<i>Anas crecca</i> : Green-winged Teal	<i>Sterna paradisaea</i> : Arctic Tern
<i>Anas formosa</i> : Baikal Teal	<i>Sterna aleutica</i> : Aleutian Tern
<i>Anas querquedula</i> : Garganey	<i>Uria aalge</i> : Common Murre
<i>Anas penelope</i> : European Widgeon	<i>Uria lomvia</i> : Thick-billed Murre
<i>Anas americana</i> : American Widgeon	<i>Cephus columba</i> : Pigeon Guillemot
<i>Anas clypeata</i> : Shoveler	<i>Synthliboramphus antiquus</i> : Ancient Murrelet
<i>Aythya ferina</i> : Common Pochard	<i>Cyclorhynchus psittacula</i> : Parakeet Auklet
<i>Aythya marila</i> : Greater Scaup	<i>Aethia cristatella</i> : Crested Auklet
<i>Aythya collaris</i> : Tufted Duck	<i>Aethia pusilla</i> : Least Auklet
<i>Bucephala clangula</i> : Common Goldeneye	<i>Aethia pygmaea</i> : Whiskered Auklet
<i>Bucephala islandica</i> : Barrow's Goldeneye	<i>Ptychoramphus aleuticus</i> : Cassin's Auklet
<i>Bucephala albeola</i> : Bufflehead	<i>Cerorhinca monocerata</i> : Rhinoceros Auklet
<i>Clangula hyemalis</i> : Oldsquaw	<i>Fratercula corniculata</i> : Horned Puffin
<i>Histrionicus histrionicus</i> : Harlequin Duck	<i>Lunda cirrhata</i> : Tufted Puffin
<i>Somateria mollissima</i> : Common Eider	<i>Cuculus canorus</i> : Common Cuckoo
<i>Melanitta deglandi</i> : White-winged Scoter	<i>Nyctea scandiaca</i> : Snowy Owl
<i>Melanitta nigra</i> : Black Scoter	<i>Asio flammeus</i> : Short-eared Owl
<i>Mergus albellus</i> : Smew	<i>Alauda arvensis</i> : Skylark
<i>Mergus merganser</i> : Common Merganser	<i>Hirundo rustica</i> : Barn Swallow
<i>Mergus serrator</i> : Red-breasted Merganser	<i>Riparia riparia</i> : Bank Swallow
<i>Buteo lagopus</i> : Rough-legged Hawk	<i>Petrochelidon pyrrhonota</i> : Cliff Swallow
<i>Haliaeetus leucocephalus</i> : Bald Eagle	<i>Corvus corax</i> : Common Raven
* <i>Haliaeetus pelagicus</i> : Steller's Sea Eagle	<i>Troglodytes troglodytes</i> : Winter Wren
<i>Circus cyaneus</i> : Marsh Hawk	<i>Turdus obscurus</i> : Eye-browed Thrush
<i>Pandion haliaetus</i> : Osprey	<i>Turdus naumanni</i> : Dusky Thrush
<i>Falco rusticolus</i> : Gyrfalcon	* <i>Oenanthe oenanthe</i> : Wheatear
<i>Falco peregrinus</i> : Peregrine Falcon	<i>Luscinia calliope</i> : Siberian Rubythroat
<i>Falco columbarius</i> : Merlin	<i>Phylloscopus borealis</i> : Arctic Warbler
<i>Lagopus mutus</i> : Rock Ptarmigan	* <i>Muscicapa griseisticta</i> : Gray-spotted Flycatcher
<i>Grus canadensis</i> : Sandhill Crane	<i>Motacilla alba</i> : White Wagtail
<i>Haematopus bachmani</i> : Black Oystercatcher	* <i>Motacilla cinerea</i> : Gray Wagtail
<i>Charadrius hiaticula</i> : Ringed Plover	<i>Motacilla flava</i> : Yellow Wagtail
<i>Charadrius semipalmatus</i> : Semipalmated Plover	<i>Anthus spinoletta</i> : Water Pipit
<i>Charadrius mongolus</i> : Mongolian Plover	<i>Bombicilla garrula</i> : Bohemian Waxwing
<i>Pluvialis dominica</i> : American Golden Plover	<i>Leucosticte tephrocotis</i> : Gray-crowned Rosy Finch
<i>Arenaria melanocephala</i> : Black Turnstone	<i>Fringilla montifringilla</i> : Brambling
<i>Arenaria interpres</i> : Ruddy Turnstone	<i>Acanthis flammea</i> : Common Redpoll
<i>Numenius phaeopus</i> : Whimbrel	* <i>Junco hyemalis</i> : Slate-colored Junco
<i>Numenius tahitiensis</i> : Bristle-thighed Curlew	<i>Melospiza melodia</i> : Song Sparrow
<i>Numenius madagascariensis</i> : Far Eastern Curlew	<i>Calcarius lapponicus</i> : Lapland Longspur
<i>Tringa glareola</i> : Wood Sandpiper	<i>Plectrophenax nivalis</i> : Snow Bunting
	<i>Emberiza rustica</i> : Rustic Bunting

*Species not observed during this study but recorded or collected by others.

Fig. 1—Ecological profile of Amchitka Island.

streams on the lower parts of the island (Fig. 2). The formation may extend out some distance from streams or boggy areas. The genera of plants in this formation are diverse but include the following herbs and ferns: *Caltha*, *Ranunculus*, *Rumex*, *Cystopteris*, *Mimulus*, *Streptopus*, *Carex*, and *Calamagrostis*.

Beach Ridges

Many of the beaches at the lower eastern end of the island are bordered on the island side by ridges of varying heights. These ridges support a characteristic plant association that separates the beaches from the tundra formations. A border of the herb *Honckenya peploides* frequently occupies the upper slope of the beach, and this in turn is bordered by a more or less distinct band of the composite *Senecio pseudo-arnica*. This composite is bordered by often extensive stands of the grass *Elymus arenarius*, especially on the higher ridges or bluffs (Fig. 3).

Coastal Reefs

Exposed lichen-spattered rocky reefs and headlands that are otherwise devoid of vegetation are characteristic of much of Amchitka's shoreline. Offshore reefs are typically covered with various species of marine algae.

Sea Beaches

The beaches of Amchitka are variously comprised of dark sand, gravel, rounded or jagged

Fig. 2—A lush stand of herbaceous vegetation along a typical riparian meadow habitat.

boulders, and piles of talus or massive angular rocks at the bases of cliffs (Fig. 4). The vegetation is sparse, although *Honckenya* is consistently found on higher areas. Windrows of kelp together with driftwood and the remains of marine invertebrates are frequently present on the lower areas.

Sea Cliffs

This formation is comprised of the steep and often sheer rocky cliffs and pinnacles (sea stacks) facing the sea around the perimeter of Amchitka. Vegetation is sparse but does include members of

Fig. 3—Beach ridge habitat showing *Honckenya* as the first plant above high tide, which in turn is replaced by *Senecio* and *Elymus*.

Fig. 4—Typical Amchitka sea beach habitat at low tide. This habitat is used by shorebirds, waterfowl, and winter wrens.

the herb genera *Draba*, *Potentilla*, and others. The tops of cliffs and pinnacles are often densely vegetated. Sea cliffs are found on about half the shoreline of the island.

Offshore Islands

The seven larger islets offshore from Amchitka are important nesting areas for some species of birds. The beaches of these islands are variously composed of massive boulders or the bases of steep and occasionally sheer rocky cliffs. The island tops have deep overlayers of soil densely covered with *Elymus*. The nesting burrows of Tufted Puffins are abundant in the deep soil on Bat, Vista, and Windy Islands and on the unnamed islet off Kirilof Point. Remains of Leach's and Fork-tailed Petrels found near or in burrows on Vista and Windy Islands suggest that these birds breed there. Bald Eagles and cormorants nest on such islets as Bat, Mex, Vista, and an islet off St. Makarius Point.

Disturbed Areas

Extensive disturbance of the tundra on the southeastern portion of Amchitka during World War II produced conditions that favored growth of distinctive localized vegetation. The most important of these disturbed areas, in terms of use by birds, are the roadside berms and the ridges encircling the deserted Quonset huts. These areas are characteristically covered with grasses (*Calamagrostis*) that provide cover for the nests of Lapland Longspurs, Mallards, and occasionally Rock Ptarmigan. There are also several colonies of Glaucous-winged Gulls whose nests are simple depressions in the grass.

The refuse dump formed a conspicuous element in the island ecosystem during the period of AEC occupation. This area has impact on the distribution only during times of human use; it was closed in 1973 when the occupation ended. It was most frequented by eagles, gulls, ravens, and rosy finches, all of which foraged on discarded meats and other food or on insects or rats attracted by the conditions at the dump. Considerable numbers of these birds frequented the dump in winter.

The seasonal populations and affinities of each species to ecological formations are given in Table 2. Some species listed as accidental have occurred on other islands in the Aleutians more frequently than was thought to be the case. Our allocation of them as accidental may be incorrect. Some species showed a primary preference for several formations in that they nested in one and foraged in another or, if migrants or visitants, occurred in several formations with equal frequency. The affinities (estimate of preference for island as a whole) of the 131 species for the

ecological formations are summarized in Table 3. Aquatic formations as well as the sea beaches were most heavily used, indicating the strong orientation of birds to the marine ecosystem. The primary preference by birds for *Empetrum*-*Cladonia* tundra, sea beaches, and marine and lacustrine waters was about equal, whereas all other formations showed very low primary preferences. This reflects the disharmonic nature of Amchitka's avifauna, a feature that is so typical of oceanic islands.

Relationship scores for 64 species were calculated with the use of the system adopted from Miller (1951) by Williamson, Thompson, and Hines (1966, p. 455) in an attempt to compare Amchitka with another tundra situation and to indicate the relationship of one formation to another with respect to their significance to birds (Table 4). Accidentals were not considered in this analysis. The visitants and most accidentals used primarily the same ecological formation on Amchitka as they do on their breeding grounds or as they do when occurring commonly in other geographic locations. This system of scoring was used for species occurring in two to five formations only since those occurring in more than five were considered too generalized in preference for relationships to be reflected. Examples of the generalized birds are Bald Eagles, Glaucous-winged Gulls, Green-winged Teal, and Gray-crowned Rosy Finch. The affinities of birds of a given formation for other formations were represented as follows: a species occurring in one additional formation was rated 0.50; in two additional formations, 0.33 for each; in three, 0.25 for each; or, if in four other formations, it scored 0.20 for each. These scores were then added to show the relationship of any two formations to one another.

Because of the relative paucity of essentially terrestrial species, the aquatic habitats take on the greatest importance. The highest score, 9.76, relates the pelagic waters to marine littoral waters and reflects not only the numbers of species in those formations but also heavy use of the formations by a common group of species. The next highest score is slightly more than half the highest score and relates the marine littoral waters to freshwater lakes and reflects the heavy use of these formations by ducks, loons, and terns. Together the three aquatic formations mentioned had the greatest importance in affinity of all the formations on Amchitka, and a rather large disparity with the other formations once again stresses the disharmonic nature of the avifauna. Relationship of sea beaches to *Empetrum*-*Cladonia* tundra had a rather high score reflecting the use of these two formations jointly by migrants.

Table 2—Estimated Seasonal Populations of Birds Found on or near Amchitka Island and Their Affinities for Ecological Formations

Species	Status*	Seasonal population†				Affinity‡											
		Spring	Summer	Autumn	Winter	Pelagic waters	Marine littoral waters	Lacustrine waters	Fluvial waters	Carex meadow tundra	Empetrum-Cladonia tundra	Alpine tundra	Riparian meadow	Beach ridge	Coastal reefs	Sea beach	Sea cliff
Common Loon	V	—§	<10	—	—	3	2	1	3								
Arctic Loon	Ac	—	Ac	—	—		1										
Red-throated Loon	B	25	100	100	—	2	1	1	3								
Horned Grebe	M	—	—	Pr	—			1	2								
Short-tailed Albatross¶	—	—	—	—	—	1											
Laysan Albatross	V	—	Pr	—	—	1	3										
Black-footed Albatross	V	—	Pr	—	—	1											
Northern Fulmar	V	Pr	Pr	? **	—	1	3										
Short-tailed Shearwater	V	?	Nu	?	?	1	3										
Scaled Petrel	Ac	—	Ac	—	—	1	3										
Fork-tailed Storm Petrel	R	Pr	Pr	Pr	?	1	2										2
Leach's Storm Petrel	R	Pr	Pr	Pr	?	1	2										2
Double-crested Cormorant	Ac	—	Ac	—	—		1										
Pelagic Cormorant	R,B	1,500	2,000	2,000	1,500	2	1								2		1 1
Red-faced Cormorant	R,B	500	800	800	500	2	1								2		1 1
Whooper Swan	V	<20	—	—	20			1		2							
Canada Goose	V	—	Co	—	—			1						2			
Black Brant	V	—	Co	—	—			1	1								
Emperor Goose	V	2,000	—	500	5,000			1		2				3	1	1	
Bean Goose	Ac	—	Ac	—	—					1							
Mallard	R,B	50	150	200	500		1	1	2				3			2	
Gadwall	V	—	Co	—	—			1	3								
Pintail††	R,B	200	50	100	200		1	1								2	
Falcated Teal	Ac	Ac	Ac	—	—			1									
Green-winged Teal	R,B	1,000	1,500	1,500	1,000		1	1	2				2		3	2	
Baikal Teal	Ac	—	Ac	—	—			1									
Garganey	Ac	Ac	—	—	—			1									
European Widgeon	V	<20	<20	<20	—		2	1									
American Widgeon	V	Co	Co	—	—			1	3							3	
Shoveler	V	<10	—	<10	—			1									
Common Pochard††	V	<10	<10	—	—			1									
Greater Scaup	R,B	150	200	150	150		2	1							3		
Tufted Duck††	V	<25	<25	—	—			1									
Common Goldeneye	R	100	10	50	4,000		1	1									
Barrow's Goldeneye	Ac	Ac	Ac	—	—			1									
Bufflehead	R	50	10	1,000	2,000		1	1									
Oldsquaw	V	—	—	—	50		3	1									
Harlequin Duck	R	1,500	500	2,500	2,500			1							2		
Common Eider	R,B	1,000	1,500	500	200			1						2	1	2	
White-winged Scoter‡‡	M,R	<10–100	<10–200	<10	<10–200	3	1										

(Table continues on page 234.)

Table 2 (Continued)

Species	Status*	Seasonal population†				Affinity‡														
		Spring	Summer	Autumn	Winter	Pelagic waters	Marine littoral waters	Lacustrine waters	Fluvial waters	Carex meadow tundra	Empetrum-Cladonia tundra	Alpine tundra	Riparian meadow	Beach ridge	Coastal reefs	Sea beach	Sea cliff	Offshore islands	Disturbed areas	Refuse dump
Black Scoter	V	<10	<20	<10	—	3	1													
Smew	V	Co	Co	—	<10		1	1												
Common Merganser	V	?	—	?	10		2	1												
Red-breasted Merganser	R,B	<50	<50	<50	<100		2	1												
Rough-legged Hawk	Ac	Ac	Ac	—	—					1										
Bald Eagle	R,B	230	230	280	<300					3	2	3				1	1	1		2
Steller's Sea Eagle	Ac	Ac	—	—	—					1										
Marsh Hawk	V	Co	—	Co	—					1	2									
Osprey	Ac	Ac	—	Ac	—											1				
Gyr Falcon	R	<10	<5	<5	<10					1	1	2								
Peregrine Falcon	R,B	50	50	75	50	3	2	2		2	1					1	1	2		
Merlin	M	Ac	—	Ac	—											1				
Rock Ptarmigan	R,B	1,400	1,400	2,800	2,500					3	1	3	1	2						
Sandhill Crane	M	Co	—	Co	—						1		1	2						
Black Oystercatcher	R,B	200	300	300	200										1	1		2		
Ringed Plover	Ac	Ac	—	—	—											2			1	
Semipalmated Plover	Ac	Ac	—	—	—											2			1	
Mongolian Plover	Ac	Ac	Ac	—	—											1				
American Golden Plover	V	50	—	50	—					2	1				3	1				
Black Turnstone	Ac	Ac	—	—	—						1									
Ruddy Turnstone	V	100	—	500	—					2	1					1				
Whimbrel	M	Co	Co	—	—						1					1				
Bristle-thighed Curlew	Ac	Ac	Ac	—	—											1				
Far Eastern Curlew	Ac	—	—	Ac	—						2				1					
Wood Sandpiper††	M,B	20	20	—	—						1		1			2			2	
Wandering Tattler	V	50	—	100	—				2						2	1				
Polynesian Tattler	Ac	Ac	Ac	—	—											1				
Lesser Yellowlegs	Ac	Ac	—	—	—								1							
Rock Sandpiper	R,B	2,500	3,000	3,500	3,000				2	1	1				2	1		3		
Sharp-tailed Sandpiper	M	—	—	50	—						1					1				
Pectoral Sandpiper††	M	10	—	100	—											1				
Baird's Sandpiper	M	—	Co	—	—											1				
Least Sandpiper	M	Ac	—	—	—											1				
Long-toed Stint	Ac	Ac	—	—	—								1			1				
Dunlin	M	Co	—	—	—											1				
Ruff	Ac	Ac	—	—	—						2		1							
Bar-tailed Godwit	V	<10–200‡‡	—	—	—						2					1				
Black-tailed Godwit	Ac	Ac	—	—	—											1				

Table 2 (Continued)

Species	Status*	Seasonal population†				Affinity‡														
		Spring	Summer	Autumn	Winter	Pelagic waters	Marine littoral waters	Lacustrine waters	Fluvial waters	Carex meadow tundra	Empetrum-Cladonia tundra	Alpine tundra	Riparian meadow	Beach ridge	Coastal reefs	Sea beach	Sea cliff	Offshore islands	Disturbed areas	Refuse dump
Sanderling	M	<10	—	?	—											1				
Red Phalarope	V	Pr	Pr	Pr	—	2	1													
Northern Phalarope	M,B	—	50	—	—		2	1					3							
Pomarine Jaeger	M	Co	—	—	—	1	1													
Parasitic Jaeger	M,B	10	50	?	—		1	2		2	1		3							
Long-tailed Jaeger	Ac	Ac	—	Ac	—		1				2									
Glaucous Gull	V	?	—	?	50		3								2	1				2
Glaucous-winged Gull	R,B	4,000	4,000	5,000	4,000	3	1	1			1				2	1		1	2	2
Black-headed Gull	V	Co	—	—	—											1				
Black-legged Kittiwake	R?	Pr	Pr	Pr	?	1	1								3			3		
Red-legged Kittiwake	R?	Co	?	Co	?	1														
Arctic Tern	M,B	50	500	—	—	2	1	1							3	3				
Aleutian Tern	M,B	50	500	—	—	1	1	2							3					
Common Murre	R?	<10	<10	Pr	?	1	1													
Thick-billed Murre	R?	<10	<10	Pr	?	1	1													
Pigeon Guillemot	R,B	50	200	50	10	2	1													
Ancient Murrelet	R	500	Pr	?	?	1	1													
Parakeet Auklet	R	Pr	Pr	Pr	?	1	1													
Crested Auklet	R	Nu	Nu	Pr	Pr	1	1													
Least Auklet	R	Nu	Nu	Pr	Pr	1	1													
Whiskered Auklet	R	Pr	Pr	?	?		1													
Cassin's Auklet	R?	Ac	—	—	—		1													
Rhinoceros Auklet	V?	Ac	—	—	—		1													
Horned Puffin	R,B	100	200	50	?	1	1										2	2		
Tufted Puffin	R,B	1,200	4,000	500	?	1	1										2	2		
Common Cuckoo	Ac	Co	Co	—	—									1		1			1	
Snowy Owl††	V	2	2	2	?					1	1									
Short-eared Owl	M	10	—	—	—					1	1									
Skylark	Ac	Ac	Ac	—	—								1			1			2	
Barn Swallow	Ac	—	Ac	—	—											1				
Bank Swallow	Ac	Ac	—	Ac	—						1								1	
Cliff Swallow	Ac	Ac	—	—	—											1				
Common Raven††	V	10	10	10	?					3	1	1				2	3			1
Winter Wren	R,B	700	1,000	1,200	700								3	1		1	1			
Eye-browed Thrush	Ac	Ac	—	—	—						1					1				
Dusky Thrush	Ac	Ac	—	—	—											1				
Wheatear	Ac	Ac	—	—	—											1				
Siberian Rubythroat	Ac	Ac	—	—	—						1					1				
Arctic Warbler	Ac	Ac	Ac	—	—									1					1	

(Table continues on page 236.)

Table 2 (Continued)

Species	Status*	Seasonal population†				Affinity‡														
		Spring	Summer	Autumn	Winter	Pelagic waters	Marine littoral waters	Lacustrine waters	Fluvial waters	Carex meadow tundra	Empetrum-Cladonia tundra	Alpine tundra	Riparian meadow	Beach ridge	Coastal reefs	Sea beach	Sea cliff	Offshore islands	Disturbed areas	Refuse dump
Gray-spotted Flycatcher	Ac	Ac	—	—	—														1	
White Wagtail	V	Co	Co	—	—								1						1	
Gray Wagtail	Ac	Ac	—	—	—											1				
Yellow Wagtail	V	Co	Co	—	—								1			1				
Water Pipit	V	Co	Co	—	—					1		2			1					
Bohemian Waxwing	Ac	—	—	Ac	—					1										
Gray-crowned Rosy Finch	R,B	1,800	2,000	2,500	2,000					3	2	2	3	2		1	1		1	3
Brambling	Ac	Ac	—	—	—									1		1				
Common Redpoll	V	Co	Co	Co	—								2						1	
Slate-colored Junco	Ac	Ac	—	—	—															
Song Sparrow	R,B §§	10	10	10	10									1						
Lapland Longspur	M,B	20,000	40,000	30,000	—					1	1		1	2		3			3	
Snow Bunting	R,B	2,000	2,000	2,500	2,000					3	1		2				2		3	
Rustic Bunting	Ac	Ac	—	—	—									1						

*M, migrant; B, breeder; R, resident; V, visitant; Ac, accidental.

†Spring (March–May); summer (June–August); autumn (September–November); winter (December–February); Ac, accidental, having occurred once or twice; Co, casual, occurring at irregular intervals in small numbers; Pr, present; Nu, numerous.

‡1, 2, 3, primary, secondary, and tertiary affinities of the birds for the formation.

§Dash indicates either that the species does not occur or that we have no data.

¶No recent data.

**Question mark indicates that the species may occur on or near Amchitka, based on its status in the Aleutians during the particular season, but we have no precise observations.

††Numbers vary from year to year.

‡‡Numbers vary from year to year or during the course of one season by the magnitude of the numbers shown.

§§Breeds on offshore islands only.

Our highest score was nearly twice that for the Cape Thompson region (Williamson et al., 1966), another Alaskan tundra region adjacent to a marine environment but on the mainland. Many of the scores for Cape Thompson showed relatively greater affinity between the various tundra formations and aquatic formations than did the Amchitka values. Of interest, however, was the relatively greater affinity between *Carex* meadow and *Empetrum-Cladonia* tundras on Amchitka than that between any of the tundra types at Cape Thompson.

The scores derived from such an analysis consist of a species number component and a

habitat restriction component. The former component would seem to most strongly reflect zoogeographic affinity, and the latter component reflects ecological affinity. Because of differential importance of these two components on a species by species basis, we suggest that a critical reconsideration and reanalysis of Miller's original affinity index may be in order. Such a task, however, is beyond the scope of this chapter.

Seasonal population estimates given in Table 2 apply to the island as a whole and in some cases are rough estimates only. Of the regularly occurring species, some 14 (Table 5) inhabit the marine pelagic waters, and we have very little population

Table 3—Summary of Affinities of Birds for Ecological Formations

Ecological formation	Species using formation	Species with primary preference for formation (excluding accidental)	Species with primary preference for formation (including accidental)
Marine habitats			
Pelagic waters	32	19	20
Marine littoral waters	52	34	38
Beach ridges	15	2	7
Coastal reefs	17	3	4
Sea beaches	52	26	41
Sea cliffs	10	6	6
Offshore islands	13	5	5
Freshwater habitats			
Lacustrine waters	31	24	28
Fluvial waters	9	0	0
Terrestrial habitats			
<i>Carex</i> meadow tundra	13	5	5
<i>Empetrum-Cladonia</i> tundra	35	18	25
Alpine tundra	6	2	2
Riparian meadow	19	7	11
Man-made habitats			
Disturbed areas	14	3	9
Refuse dump	5	1	1

Table 4—Relationship Scores for Ecological Formations As Indicated by Occurrence of Birds

	PW	MLW	LW	FW	CMT	ECT	AT	RM	BR	CR	SB	SCI	OI	DA
Pelagic waters (PW)		9.76	0.95	0.50				0.20		1.10	0.20	0.90	1.81	
Marine littoral waters (MLW)	9.76		5.84	0.70	0.20	0.20		0.73	0.45	2.63	1.43	0.90	1.81	
Lacustrine waters (LW)	0.95	5.84		1.03	0.20	1.20		0.73	0.50	0.88	0.73			
Fluvial waters (FW)	0.50	0.70	1.03					0.20		0.33	0.86			
<i>Carex</i> meadow tundra (CMT)		0.20	0.20			2.96	0.73	0.40	0.20		0.73			
<i>Empetrum-Cladonia</i> tundra (ECT)		0.20	1.20		2.96		0.93	0.65	0.33	0.40	2.01			0.45
Alpine tundra (AT)					0.73	0.93		0.20	0.40		0.40	0.20		0.20
Riparian meadow (RM)	0.20	0.73	0.73	0.20	0.40	0.65	0.20		0.55		1.53	0.25		1.00
Beach Ridges (BR)		0.45	0.50		0.20	0.33	0.40	0.55		0.45	1.03	0.45		0.20
Coastal reefs (CR)	1.10	2.63	0.88	0.33		0.40			0.45		1.76		0.33	
Sea Beaches (SB)	0.20	1.43	0.73	0.86	0.73	2.01	0.40	1.53	1.03	1.76		0.25	0.66	0.33
Sea Cliffs (SCI)	0.90	0.90					0.20	0.25	0.45		0.25		0.90	0.20
Offshore islands (OI)	1.81	1.81								0.33	0.66	0.90		
Disturbed areas (DA)						0.45	0.20	1.00	0.20		0.33	0.20		

Table 5—Birds Regularly Inhabiting the Pelagic Waters Around Amchitka (Size of Populations Not Known)

Black-footed Albatross	Common Murre
Laysan Albatross	Thick-billed Murre
Northern Fulmar	Ancient Murrelet
Short-tailed Shearwater	Parakeet Auklet
Fork-tailed Storm Petrel	Crested Auklet
Leach's Storm Petrel	Least Auklet
Black-legged Kittiwake	Whiskered Auklet

information on them since there were few opportunities to travel more than 1 or 2 miles offshore. The other species inhabit either the island proper or its nearshore littoral waters.

About 35,000 birds occupy the tundra and the freshwater lakes and streams on Amchitka at the beginning of the breeding season; about 20,000 of these are Lapland Longspurs. About 15,000 birds inhabit the sea beaches (including cliffs, sea stacks,

and offshore islands) and the marine littoral waters; Tufted Puffins and Glaucous-winged Gulls represented more than half of these. Thus some 50,000 birds occur on or near Amchitka at the beginning of each breeding season.

The terrestrial and freshwater birds decrease to about 6500 in winter. This decrease represents mainly the departure of the Lapland Longspurs and the forced departure of most of the ducks owing to the freezing of freshwater lakes. Thus about 30,000 birds occur on or near Amchitka during the winter months.

ESTIMATES OF BREEDING POPULATIONS

Estimates of total island populations of breeding birds were based on direct counts of individuals and pairs in representative census plots for Lapland Longspurs, Rock Sandpipers, and Rock Ptarmigan. Data from the census plots were extrapolated to give estimated island populations. Eagles, falcons, and cormorants have rather specific nesting localities around the perimeter of the island and were censused during the breeding season from land vehicles or from a helicopter. For species of more general or irregular distribution, such as gulls, breeding populations were estimated on the basis of observations made as opportunity occurred.

The most reliable estimates (based on repeated censuses) of breeding populations were obtained for only 7 (Lapland Longspur, Rock Sandpiper, Pelagic Cormorant, Red-faced Cormorant, Rock Ptarmigan, Peregrine Falcon, and Bald Eagle) of the 28 species known to breed on the island. These few species, however, comprise about 70% of the total breeding population. Lapland Longspurs, for example, make up more than half the breeding birds on Amchitka.

Table 6 gives the estimates of numbers of breeding pairs for all species known to use Amchitka as a breeding ground. The numbers tabulated (except for those for the two raptor species and colonial nesting species) are not as well documented as those based on data from census plots. They are, however, the best estimates available, and they are based on numerous observations made over several seasons. Table 7 gives the periods of nesting activity for breeding species. Additional data on the species studied most intensively are given in the following sections.

Lapland Longspur and Rock Sandpiper Censuses

Between May 15 and 30, 1968, census plots were established in selected terrestrial ecological formations preliminarily considered to be important bird nesting habitats. Four ecological

Table 6—Estimates of Numbers of Breeding Amchitka Birds

Species	Number of breeding pairs
Lapland Longspur	19,000
Rock Sandpiper	1,500
Gray-crowned Rosy Finch	1,000
Snow Bunting	1,000
Glaucous-winged Gull	1,000
Tufted Puffin	1,000
Pelagic Cormorant	750
Rock Ptarmigan	700
Common Eider	700
Winter Wren	500
Green-winged Teal	300
Red-faced Cormorant	250
Arctic Tern	150
Black Oystercatcher	100
Aleutian Tern	100
Greater Scaup	75
Pigeon Guillemot	75
Bald Eagle	60
Horned Puffin	75
Mallard	50
Pintail	25
Red-breasted Merganser	25
Northern Phalarope	25
Red-throated Loon	25
Parasitic Jaeger	20
Peregrine Falcon	20
Song Sparrow	10
Wood Sandpiper	10
Total for 28 species	28,485

formations with their characteristic plant community types were staked off for intensive censusing during the breeding season. Censuses were carried out in three of the plots during the 1968, 1969, and 1970 nesting seasons; the fourth plot, on a beach ridge, was abandoned after repeated observations in 1968 revealed no nesting birds in it.

The four plots, located in the southeastern part of the island (Fig. 5), can be described as follows:

1. *Empetrum*—*Cladonia* tundra (Fig. 6). This is the most abundant vegetation type on Amchitka. It occupies the well-drained upland areas and is characterized by *Empetrum nigrum*, *Cladonia pacifica*, and *Loiseleuria procumbens*. The vegetation is generally low, but lush growths of *Empetrum* occur on the steeper hillsides and on the sides of ravines, both of which are well drained. Forty-nine acres of this vegetation type near Silver Salmon Lake were selected for the study area.

2. Riparian meadow. This formation includes the dense lush stands of herbaceous vegetation bordering many of the larger streams on the island. The genera of plants comprising this formation

Table 7—Months During Which Eggs and/or Young Are Present in Nests on Amchitka Island

Species	Month					
	Mar.	Apr.	May	June	July	Aug.
Red-throated Loon				X	X	
Pelagic Cormorant			X	X	X	
Red-faced Cormorant			X	X	X	
Mallard			X	X	X	
Pintail				X	X	
Common Teal			X	X	X	
Greater Scaup				X	X	
Common Eider				X	X	
Red-breasted Merganser				X	X	
Bald Eagle	X	X	X	X	X	X
Peregrine Falcon		X	X	X	X	
Rock Ptarmigan				X	X	
Black Oystercatcher			X	X		
Wood Sandpiper				X	X	
Rock Sandpiper			X	X		
Northern Phalarope				X	X	
Glaucous-winged Gull			X	X	X	
Arctic Tern				X	X	
Aleutian Tern				X	X	
Parasitic Jaeger				X	X	
Pigeon Guillemot			X	X	X	X
Horned Puffin				X	X	
Tufted Puffin				X	X	
Winter Wren				X	X	X
Gray-crowned Rosy Finch			X	X	X	
Song Sparrow*						
Lapland Longspur				X	X	
Snow Bunting				X	X	
Total	1	2	11	27	25	3

*No data.

include *Caltha*, *Ranunculus*, *Rumex*, *Cystopteris*, *Mimulus*, *Streptopus*, and *Calamagrostis*. Generally this lush and diverse vegetative formation extends 20 to 30 ft on either side of the stream and then is replaced by a lower but nonetheless lush formation consisting of *Carex*, *Calamagrostis*, and *Cladonia*. Thus the riparian meadow formation also includes a *Carex* meadow formation. Although the total area covered by this type of formation is small compared with that of the upland tundra formations, it is a very important nesting habitat for longspurs and sandpipers. The 10-acre census plot included the habitat disturbance created by tracked vehicles traveling through it (Fig. 7).

3. *Carex* meadow tundra. This formation is second in abundance to the *Empetrum*–*Cladonia* tundra and is usually found in lake and pond regions where there is little relief and poor drainage. This formation might be considered as inter-

mediate between the *Empetrum*–*Cladonia* tundra and the riparian meadow. The vegetation is low, consisting mainly of *Cladonia pacifica* and various species of the genus *Carex*. *Empetrum nigrum* is generally absent, as are the more lush herbaceous plants found in the riparian meadow. The 13-acre *Carex* meadow plot contains several small ponds and borders two large lakes.

4. Beach ridge. Between most of the sea beaches and tundra formations is a narrow ridge characterized by lush stands of *Elymus arenarius*, which in late summer attain heights of 4 to 5 ft. A border of *Honckenya peploides* frequently occupies the upper slope of the beach, which in turn is bordered by a more or less distinct band of *Senecio pseudo-arnica*. Usually this total strip is less than 35 yards wide, but it is characteristically present around the entire perimeter of the island. During the 1968 nesting season, a plot 630 yards

Fig. 5—Location of plots used for censusing Lapland Longspurs and Rock Sandpipers (numbered dots) and Rock Ptarmigan (hatched area). Nine major lakes used in censusing waterfowl are also shown. (Vegetation of numbered plots: 1, *Empetrum-Cladonia* tundra; 2, Riparian meadow; 3, *Carex* meadow tundra; 4, Beach ridge.)

long and 35 yards wide in this formation was censused and found to contain no nesting birds, and thus censusing was not continued in it.

The population data collected in the longspur and sandpiper census plots during the three nesting seasons are given in Table 8 as pairs per 100 acres. From these data the following weighted average densities in all types of breeding habitat were calculated for the two species: 37 pairs of Lapland Longspurs and 3 pairs of Rock Sandpipers per 100 acres. These values were then used to estimate the total island populations.

The area of the island covered primarily by *Empetrum-Cladonia* tundra, riparian meadow, and *Carex* meadow tundra is located on the lower elevations comprising the eastern three-fifths of the island. The higher elevations of the western two-fifths of the island are characteristically wind-

swept, contain expanses of bare gravel largely devoid of vegetation, or present a mosaic of vegetated and bare areas. Most of this area is not used by nesting birds, although the valleys of this area and the extreme western tip of the island contain vegetation more conducive to nesting.

The area of the eastern three-fifths of the island is about 45,000 acres. Thus we estimated that about 16,000 pairs of Lapland Longspurs and 1,300 pairs of Rock Sandpipers nest in that portion. Of the total area of the western two-fifths of the island (about 31,500 acres), only about 7,900 acres are used for nesting. About 3,000 pairs of longspurs and 200 pairs of sandpipers breed there. On the basis of census data (1968, 1969, and 1970) and island acreage of suitable nesting habitat, the total Lapland Longspur population nesting on Amchitka was estimated to be about 38,000 individuals (19,000

Fig. 6—Census plot in the upland *Empetrum*–*Cladonia* habitat. Drilling rig used on Milrow project shows on the skyline.

Fig. 7—The riparian meadow study-plot area at Bridge Creek. This habitat was most heavily used by breeding Lapland Longspurs and Rock Sandpipers.

Table 8—Numbers of Nesting Pairs of Lapland Longspurs and Rock Sandpipers per 100 Acres, in Different Ecological Formations, Based on Extrapolation from Counts made in Census Plots

	Number of pairs per 100 acres					
	Lapland Longspurs			Rock Sandpipers		
	1968	1969	1970	1968	1969	1970
<i>Empetrum-Cladonia</i> tundra	22	16	16	2	2	2
Riparian meadow	100	110	100	0	10	0
<i>Carex</i> meadow tundra	40	40	40	8	8	16

pairs). The estimated total Rock Sandpiper nesting population was about 3,000 individuals (1,500 pairs).

Breeding Phenology: Lapland Longspur. Earlier Williamson and Emison (1971) described the breeding phenology of the longspur on Amchitka, and certain of its breeding parameters were compared to other populations (Williamson, 1968).

The arrival times of Lapland Longspurs at Amchitka are similar to those in other northern localities. The earliest sighting at Cape Thompson (Williamson et al., 1966) was on Apr. 28; on Amchitka it was on May 1. The earliest flocks to arrive were entirely or mostly composed of males. The number of females increased steadily until mid to late May when the sexes were present in approximately equal numbers. In 1969, the first female was seen on Amchitka on May 7, a marked influx of females was noted in mid-May, and the sex ratio was approximately 50 : 50 by May 26. The sequence of events was similar to that at Cape Thompson.

The timing of the principal events comprising the breeding cycle of the Lapland Longspur can be summarized as peak of nest construction, June 11; peak of egg laying, June 15; peak of incubation, June 21; and peak in nestling care activity, July 1 (Fig. 8).

Data on fledging success, considering only nests from which at least one young fledged, were obtained from a sample of 35 nests. On the average, 57% of the nests were successful, and the overwhelming percentage of nest losses was due to predation (Williamson and Emison, 1971). On the average, 3.0 young fledged per successful nesting attempt, or about 1.5 young per adult on the island. There appears to have been a subsequent loss of young from the population, perhaps by dispersion, as indicated by the age ratios of adults to juveniles observed along roadways at the end of July (Table 9).

On Amchitka small flocks of longspurs were forming in mid-August. By late August these flocks

included up to 50 birds, and migration from the island began in September. We estimated that over half the population had departed by October 1, and the last sighting was of a flock of eight birds on October 14. Kenyon (1961) observed single birds on October 17 and 19 and collected a female on November 13. If we accept October 14 as the latest usual departure time, longspurs remain 1 month longer on Amchitka than on Cape Thompson. In the 3 years of observations at the latter locality, longspurs were usually absent by September 12; one late sighting was made on September 23.

Rock Ptarmigan Censuses

May censuses of Rock Ptarmigan on a 2500-acre plot (see Fig. 2) on Amchitka provided the following record of densities: 1969, 32 pairs, and 1970, 34 pairs. In 1971 the May census was not conducted, but observations in late April and again in late June and during July indicated that the size of the breeding population was similar to that of the previous 2 years. This is a density of 6 to 7 individuals per 250 acres, which is similar to published estimates of spring population densities of Rock and Willow Ptarmigan (*Lagopus lagopus*) in Alaska and Canada (Weeden, 1963). However, the density falls on the low side when compared with spring populations in the long-term studies on Rock Ptarmigan in Scotland, which range from 5 individuals per 250 acres in low years to 15 to 18 individuals per 250 acres in high years (Watson, 1965). With the use of the population figure of 6 to 7 birds per 250 acres and the figures of total island area of suitable nesting habitat (calculated by C. C. Amundsen, University of Tennessee, personal communication) for ptarmigan, we estimated that 700 to 750 pairs (1400 to 1500 individuals) nested on Amchitka in 1969 and 1970. On the basis of these values and on the August 1969 ratio of 1.4 young to every adult bird seen, the total island population reaches a maximum of about 3500 individuals in this month.

Fig. 8—Schematic representation of the breeding phenology of the Lapland Longspur from arrival in May to average departure in September.

Table 9—Age Ratios of the Lapland Longspur, July 28, 1972

Miles in count	Adult males	Adult females	Juveniles	Unidentifiable	Adult : juvenile ratio
3.0	20	10	21	10	1.43 : 1
3.1	10	3	12	7	1.08 : 1
2.0	10	7	16	6	1.06 : 1
Total	8.1	40	49	23	1.23 : 1

Breeding Phenology: Rock Ptarmigan. Data gathered from observations of behavior, nests, and broods and from gonad examinations of collected adults indicate that onset of egg laying and subsequent chick hatching are rather synchronous within the Amchitka population. Most females begin egg laying about mid-June and lay an average of 9.2 eggs (9 nests; range, 7 to 14 eggs). The hatching peak of about mid-July is 1 to 3 weeks later than that reported for central Alaska (Weeden, 1963) and is about 3 weeks to 1 month later than those of Rock Ptarmigan in Scotland and Iceland (Watson, 1965; Gardarsson and Moss, 1970).

By late July some broods are capable of flight, and during August females with fledged broods are common on the tundra. At this time counts reveal an average of 5.0 young per brood (range, 1 to 12). Between Aug. 18, and Sept. 2, 1969, counts of all ptarmigan seen (82 individuals) on the low plateaus

revealed a ratio of 1.4 young to 1 adult bird. This difference between the expected ratio (2.5 young to 1 adult, based on the average brood size) and the observed ratio (1.4 young to 1 adult) probably indicates that some females are unsuccessful or that a surplus of adult breeding males is present or both.

Winter Movements. Flock formation occurs in September with integration of all components of the population into the flocks. Flock size is small and averages 10 birds or less (range, 1 to 50) per flock during any autumn or winter month. Apparently, at least during some winters, there is a gradual movement of birds from the breeding areas on the low plateaus up into the alpine tundra region of the mountains. The factors influencing this movement are unclear but may be related to snow cover in the lower elevations, food selection, or winter population density. This is a partial

movement involving both sexes, with some small flocks containing nearly equal numbers of males and females remaining on the low plateaus for the entire winter. Most males leave the mountains in April and move down to the low plateau breeding areas where they mingle with the males and females that remained in this area through the winter. Thus a partial sex separation exists for a short time during late April when counts reveal a 3 male to 1 female ratio on the low plateaus and a 1 male to 9 female ratio for those birds (now in flocks of up to 300 birds) remaining in the mountains. The females soon follow and by early May have joined the males on the low plateaus.

The age ratio (3 young birds : 1 old bird) of 43 winter (November through March) specimens collected on the low plateaus was considerably different from the 1.4 : 1 ratio observed during August after chick fledging and the 1.1 : 1 ratio obtained from 40 birds collected in the same areas during late April through July. This high winter ratio of young to old birds on the low plateaus suggests that a larger proportion of old birds are involved in the movement to the higher elevations, although a few remain on the low plateaus throughout the winter.

Winter Wren Counts

The *Elymus* stands along the edge of the beaches and on the steep hillsides adjacent to the beaches form a conspicuous habitat occupied by

the Winter Wren. The wrens were reported to be very plentiful on Amchitka in 1870 (Dall, 1874) and particularly common in 1937 (Kenyon, 1961). However, Kenyon found only one wren on Amchitka between 1955 and 1959 and suggested that they had been eliminated from the island. Because there appeared to have been a comeback of wrens since Kenyon's surveys, 17 sections of beach totaling 25 miles (40 km) were walked (Fig. 9) to obtain estimates on the present size of the wren population on Amchitka. The results of these censuses are shown in Table 10.

Generally the densities were relatively high along beaches adjacent to the high country where precipitous cliffs tower above the water's edge. The wrens are in the numerous small crevices and caves of these rocky areas. In lower areas the densities are variable. The long sandy beaches bordered with *Elymus* and *Senecio* but with no nearby rocky cliffs had only one or two birds per mile. However, other areas in the low country where there are cliffs or boulder beaches had densities comparable to those in the high country.

The 25 miles (40 km) walked resulted in an average count of four to five per mile. Although wrens are nearly always found along the beach, they were seen on two occasions about half a mile inland. This was in marked contrast to Semisopochnoi Island where wrens were seen along the stream coming out of Fenner Lake, about 5 miles (8 km) inland from the beach.

Fig. 9—Sections of beach (stippled and numbered) used in censusing Winter Wrens.

Table 10—Winter Wrens Observed per Mile on Selected Sections of Amchitka Beach

Section of beach walked (Fig. 3)	Wrens per mile	Section of beach walked (Fig. 3)	Wrens per mile
1	0	10	10
2	4	11	8
3	12	12	1
4	1	13	1
5	1	14	1
6	7	15	8
7	16	16	6
8	12	17	6
9	7		

Although wrens have made a "comeback" on Amchitka, they are not as common as they are on some islands. If indeed mammalian predation (by rats and foxes) did cause the presumed elimination of the wrens, unfortunately no data exist on their density prior to the introduction of these two mammals. Buldir Island, one of the few islands where rats and foxes have never been, had 15 wrens in 1000 yards of beach (26 per mile) on the northwest side of the island in late June (White, personal observation).

Colonial Bird Censuses

Both Glaucous-winged Gulls and cormorants are conspicuous elements of the Amchitka avifauna. These species are also rather easy to census, and some data were obtained on their biology and population dynamics, although we could not devote sufficient time to their study to obtain the kinds of data on cliff nesting species that were obtained at Cape Thompson by Swartz (1966).

Pelagic and Red-Faced Cormorants. Censuses made from a helicopter in June and July 1968 revealed 23 nesting colonies around the perimeter of the island and on offshore islets. Most of these contained 10 to 30 nests, whereas the largest, by actual count, contained 60 nests. (See Figs. 10 and 11.)

Censuses from the helicopter in May and June 1969 revealed 17 colonies (possibly 3 were missed in the Ivakin Point area and on Bat Island, as suggested by later counts). Of these, 11 contained between 10 and 30 nests. Of the remaining 6 colonies, one contained only 2 nests and one had only 1 nest. The Mex Island colony was the largest, with about 85 nests. A colony in Chitka Cove contained 36 nests (all Pelagic Cormorants), and the colony at Kirilof Point contained 33 nests (18 Pelagic and 15 Red-faced Cormorants). The loca-

tions of all the colonies found in 1968 and 1969 are shown in Fig. 12.

Apparently in some mixed colonies the Red-faced Cormorants place their nests higher on the average than the Pelagic Cormorants. This was especially noticeable in 1969 at Mex Island. In 1971 this colony had 29 Red-faced and 35 Pelagic Cormorant nests, whereas in 1973 there were 34 Red-faced and 23 Pelagic Cormorant nests. In 1973 this colony had an unusually high mortality and abandonment. Of the 57 starting nests on May 18 (all on eggs), only 10 Pelagic and 14 Red-faced

Fig. 10—Pelagic Cormorants on World War II dock pilings in Constantine Harbor.

Fig. 11—Cormorant nesting colony on "Cat" rock which contains both Red-faced and Pelagic Cormorant nests.

Fig. 12—Locations of colonies of breeding cormorants, 1968–1969.

Cormorant nests (some with young) remained on June 5. At least five dead adults were found on the hillside and beach where they had been preyed upon by eagles. On June 17 no birds remained at the colony. In 1973 cormorants had poor reproduction and high mortality in other parts of the Pacific Ocean (D. Ainley, personal communication). On Farallon Island nest abandonment and poor reproduction in Pelagic Cormorants were directly attributable to extremely low numbers of the major fish species that are the prime food item of cormorants there. Low cormorant food resources throughout parts of the Aleutians might likewise have caused poor reproduction on Amchitka.

On the assumption that an average-size colony contained 25 nests and there were 20 colonies located around the island, the breeding population for 1969 was about 1000 birds (500 pairs). Some of these colonies were composed only of Pelagic Cormorants and others of both Pelagic and Red-faced Cormorants. No pure colonies of Red-faced Cormorants were located.

Colony sites can change in consecutive years. Only 9 of 23 colonies located in 1968 were in the same area in 1969. Three colonies active in 1968 were examined in 1969, and, although nests were still visible, they were unoccupied. There was also a

shift in species composition within some of the colonies from 1968 to 1969. For example, the colony on Kirilof Point was composed of about 90% Pelagic Cormorants in 1968, whereas in 1969 it contained nearly 50% Red-faced Cormorants.

Glaucous-Winged Gulls. The location of gull colonies on Amchitka changed little between 1968 and 1969 (Fig. 13), hence no effort was made to distinguish those found in 1968 from those found in 1969. The only apparent shift was the abandonment of the Vista Islet colony, which contained five nests in 1968 and none in 1969. Most of the colonies were situated on upland *Empetrum*–*Cladonia* tundra formation, although isolated nests were found in stands of *Elymus* just above the sea beaches. Frequently solitary nests were found on the tundra or the colony was simply a rather diffuse aggregation of solitary nests.

Censuses of Freshwater Aquatic Birds

Nine lakes on the eastern third of Amchitka were selected for censusing aquatic birds in freshwater habitats; the location of the lakes is shown in Fig. 5. During 1967 to 1969, each lake was visited regularly, and the number of each species of waterfowl present was recorded. Censuses were made during February, April, May, June, July,

Fig. 13—Locations of Glaucous-winged Gull colonies, 1968–1969.

August, September, and October, but data for February, April, and August are scant. The number of visits to each lake by year and month and the average number of individuals of each species seen per month are given in Tables 11 and 12, respectively. Estimates of breeding populations of species using the lacustrine habitat for nesting (Red-throated Loon, Mallard, Pintail, Green-winged Teal, Greater Scaup, Red-breasted Merganser, and Northern Phalarope) are given in Table 6.

In addition to the 17 species of aquatic birds observed on the lakes censused (Table 12), the Garganey, the American Widgeon, and the Northern Phalarope were observed on other freshwater ponds.

With the data given in Table 12, supplemented by those from observations on other lakes, seasonal movements and population fluctuations of these

species can be determined. Their status on the island is given below.

The Horned Grebe, Canada Goose, Brant, Green-winged Teal (North American subspecies), European Widgeon, Common Pochard, and Smew were accidental visitors to the island and occurred in small numbers. The European Widgeon was seen courting and copulating, but proof of breeding was not obtained. The Shoveler was a regular spring and autumn migrant but also occurred in small numbers. The Tufted Duck occurred in moderate numbers in some springs. Courtship was seen in this species, but we have no evidence of its breeding. The Common Goldeneye and Bufflehead began arriving in September and October, remained through the winter, and the bulk departed in April and May, although minor numbers remained through the summer. The Red-breasted Merganser

Table 11—Number of Censuses per Month on Nine Lakes on Amchitka Island, 1967–1969

Lake	1967			1968					1969	
	August	September	October	February	April	May	June	July	May	June
Tin			5	1	1	1			5(6)*	5(5)†
G.E.		4	5	2		2			4(6)	5(5)
Rifle Range	1	3	4	1		3			4(7)	5(5)
Clover	1	1	9	1		1			6(7)	5(5)
Mason			6	1	1	6	6	6	6(12)	7(13)
Pumphouse		2	7	1	1	1	3	7	4(5)	4(7)
Quonset						6	10	9	5(11)	5(15)
Clevenger	4	5	9	1	1	5	10	7	5(10)	6(16)
Jones	1	4	10	2		6	7	8	5(11)	5(12)

*Number in parentheses is total for May 1968 and May 1969.

†Number in parentheses is total for June 1968 and June 1969.

Table 12—Average Number of Aquatic Birds Observed per Census on Nine Freshwater Lakes, 1967–1969

Species	Feb.	April	May	June	July	Aug.	Sept.	Oct.
Common Loon				0.1	0.1			
Red-throated Loon			0.2	0.3	0.7	1.4		
Horned Grebe								0.1
Canada Goose			0.1					
Brant								0.1
Mallard		0.5	0.7	0.5	0.5	1.0	8.6	8.4
Pintail		0.3	0.1	0.1	0.1		0.4	1.7
Green-winged Teal	5.0	3.0	0.8	1.7	5.9	8.0	35.4	30.8
European Widgeon								0.4
Shoveler			0.1				1.0	0.2
Common Pochard			0.1	0.1				
Greater Scaup	4.0	0.3	5.8	6.1	5.2	1.7	16.0	9.8
Tufted Duck			0.6	0.2				
Common Goldeneye	0.4	0.5	0.7	0.7	0.5		0.4	1.4
Bufflehead	5.3	4.8	4.5	0.2				1.4
Red-breasted Merganser		1.3	1.0	0.4	0.1		0.2	0.2
Smew				0.1				

was a year-round resident with fairly constant numbers. The decline in number observed during the summer and autumn was a result of the females becoming inconspicuous while incubating and caring for their young. The Red-throated Loon appeared in May and was resident (breeding) through August. The Common Loon was present in June and July in pairs but, although they were seen in courtship, nests were never found, although one or two pairs may breed there in some years.

The Mallard, Pintail, Green-winged Teal (Eurasian form), and Greater Scaup were year-round residents. The number of adults on the lakes censused was low in spring and summer while breeding was taking place on the many small lakes and ponds about the island. In autumn, Mallards gathered in large flocks on many of the lakes censused, and the average number of individuals observed per census was much higher than in spring and summer. Data indicate that there was an autumn migration of Mallards and possibly an early spring migration. Also, there was a definite spring and autumn influx of Pintails which enlarged the population. The large increase in teal and scaup populations in the autumn appears only to be the result of local movements of large flocks onto the lakes censused rather than any migratory influx of individuals. Although all these species spent some time on salt water, their preference for freshwater ponds and lakes, when these were not frozen, was clearly indicated.

Only a fraction of the many lakes and ponds on Amchitka are used by waterfowl as feeding and loafing places in the fall before the first permanent freezing of freshwaters. There are about 2500 lakes and ponds on the island, the largest of which is about 1000 yards long and 400 yards wide. The most complete autumn survey for waterfowl was made on Oct. 23, 1971, partly by observers on foot and partly from a helicopter. Although nearly all the lakes and ponds on the island were surveyed, waterfowl were seen on only 16 lakes in the southeastern half of Amchitka (including 7 of the 9 census lakes listed in Table 11). A similar survey was made in October 1972, and waterfowl were observed on the same 16 lakes and in small numbers on 5 additional lakes. Census data from the two autumn surveys are summarized in Table 13. The surveys show that less than 1% of the freshwater lakes and ponds on Amchitka are regularly used by waterfowl during the fall.

DISTRIBUTION OF MARINE WATERFOWL

Reliable data on all the marine-inhabiting waterfowl are lacking. However, scoters proved rather easy to census since most flocks seemingly

Table 13—Total Numbers of Waterfowl Observed by Species on Amchitka Freshwater Lakes and Ponds During October Surveys*

Species	1971	1972
Mallard	301	312
Pintail	152	4
American Widgeon	2	3
Shoveler	0	5
Green-winged Teal	722	412
Greater Scaup	110	65
Red-breasted Merganser	4	8
Bufflehead	24	0
Goldeneye	2	0
Unidentified	0	19

*Waterfowl were observed on 16 lakes in 1971 and on 21 in 1972.

occurred in Constantine Harbor with White-winged Scoters greatly outnumbering Black Scoters.

The numbers present were quite variable not only between successive seasons but also between the same seasons in different years. Flocks were sighted in all months (Table 14). Over half the flocks observed were in May and June, the months of most intensive censusing. The average number of birds per flock tended to be largest during the late spring, summer, and early fall months (Table 14). From the observations made during this study, we estimated that no more than 500 individuals occur around Amchitka, and probably the number is usually considerably less than this.

Throughout this study notes were taken on the occurrence of adult males in the flocks. Of 624 individual White-winged Scoters, only 35 (less than 6%) were adult males. The rest were in the drab brown plumages of the female and the subadult. Of the 35 males seen, 30 were present in a flock of 60 birds during late May. On May 25, 1970, two birds in drab plumages collected in Kirilof Bay proved to be a male and a female, both subadults. These data suggest that most of the individuals occurring near Amchitka are nonbreeders, and this is further confirmed by the fact that neither Kenyon (1961) nor ourselves have obtained any indication that this scoter nests on Amchitka.

STUDIES OF CLIFF-NESTING RAPTORS

Population densities of cliff-nesting raptors were rather easy to determine in some years because of the use of a helicopter. There are, however, no similar studies in the Aleutians to use as a basis of comparison with these populations. The only comparable study on Bald Eagles, i.e., comparable by virtue of its proximity, is that by Hensel and Troyer (1964) for Kodiak Island. Similar populations of falcons have been studied

Table 14—Number and Average Size of Flocks of Scoters Observed Near Amchitka Between August 1967 and December 1970

Month	White-winged Scoter		Black Scoter	
	No. of flocks sighted during month	Average number per flock	No. of flocks sighted during month	Average number per flock
January	1	4	2	3
February	2	4	3	1
March	3	13	3	1
April	2	10	1	1
May	7	38	3	7
June	10	44	3	5
July	1	9	1	1
August	2	60		
September	1	60		
October	3	18	2	2
November	1	25		
December	1	8	1	5

by Beebe (1960) and Nelson (1970) on the Queen Charlotte Islands, British Columbia, although this latter locality is a heavily timbered habitat. On Amchitka we found eagles and falcons to be rather uniformly distributed around the periphery of the island.

Bald Eagle

In July 1968 three helicopter flights were made around the perimeter of the island, the locations of eagle nests were plotted, and some data on reproduction were obtained on the 40 nests located. The data were not complete enough to compare with subsequent years, however. Previously the greatest number of nests located was 35 found during a dory survey in 1962 (McCann, 1963). As work progressed on the island, a continually greater number of nests were located (Fig. 14). Eagle nest counts for 5 years are given in Table 15.

The increased number of nests found in 1969 over 1968 may have been a function of the time of year at which the surveys were made or perhaps of the greater thoroughness of searching for nests in 1969. Also, the lower number in 1968 may be a result of nest failure early in the breeding season (April and May) prior to the time censuses were made. The increase after 1969 is thought to have resulted from a greater food supply available because of the refuse dump. The lower number again in 1974 is probably due to the closing of the dump in 1973. Raptors typically show a rather high degree of nest tenacity, but one-third of the eagle nests used one year were not used the following year. The difference between 1968 and 1969 provides a good example. At least 15 nest

Fig. 14—Adult Bald Eagle swooping on an intruder to its nesting site. (Photograph by Richard Glinski.)

sites that contained young in 1968 were not used in 1969, and these represent 37.5% of all the nests located in 1968. The true percentage is probably even higher because some of the nests found in 1968 were not as precisely located (exact sea stack or cliff) as were those in 1969. Seemingly certain eagles routinely use alternative sites from year to year.

Part of the continued increase in nesting attempts from 1970 to 1972 may have resulted in

Table 15—Reproduction Data for the Bald Eagles,
1968–1972 and 1974

Description	Year					
	1968	1969	1970	1971	1972	1974
Number of nests	40	57	56	68	71	64
Percent of nests known with young	?	61	71	71	72	67
Percent of nests fledging young	?	58*	?	?	61	?

*The last data were gathered about 12 days prior to actual fledging of young, and the value given is probably too high.

an actual increase in younger eagles attempting to breed, as indicated by the fact that at least two of the nesting birds had large amounts of brown in the tails and heads which suggested that they had not reached full adult status. Because at times more than 600 persons were on the island starting in 1970 and continuing through 1971, the amount of refuse at the garbage dump presumably increased, thus giving the eagles a greater food supply. Eagles relied heavily on the garbage dump for food, especially during the winter, which in the long run may have lowered the mortality of the younger age groups and allowed a greater number of birds to reach breeding status. Our data further suggest that, at least since 1970, a preponderance of nests was located in the southeastern third of the island. In 1972, for example, there were 38 nests (53% of the total number) along only 44 miles of coastline (36% of the total coastline), which was probably due to the garbage dump being located near the southeastern end of Amchitka.

The placement of nests varied from year to year and may reflect local shifting between alternate sites. The differences can be seen in a comparison of 1968 data with 1971 data. In 1968, 35 (87.5%) of the nests were situated on sea stacks, 4 (10%) at the edge of a cliff on the main island, and 1 (2.5%) on a tundra mound. By contrast, in 1971, 39 (60.9%) were situated on sea stacks, 17 (26.6%) on ridges or stacks connected to the main island, and 8 (12.5%) near cliff edges on the main island or on small islands just offshore. (See Figs. 14 and 15.)

In 1972, a year for which data were comprehensive enough to analyze, fledging success appeared to vary in relation to the type of structure on which the nest was placed. Nests closely connected to the mainland had greater success in fledging young than those nests with restricted areas for the young, e.g., sea stacks (Table 16). Nest sites located where young could move to adjacent large areas (e.g., hillsides) appeared to promote greater nesting success than

Fig. 15—Adult Bald Eagle incubating eggs (Apr. 4, 1972).

those sites with a nesting platform of limited size on which the young can move about (e.g., most sea stacks). Since nesting success varies in relation to the physical placement of a nest, nest site selection may be an active process with eagles. Independent of size of the nesting area, however, a nest site may be selected in response to the proximity to a locally abundant food source, e.g., the refuse dump. Further, in the past less favorable nest sites may have been selected, for instance, greater use of sea stacks even though fledging success was less, because these were not accessible to such terrestrial predators as foxes following their introduction onto

Table 16—Relationship of Bald Eagle Nest Location to Fledging Success for 1972

Nest location	Number of nests	Percent of total nests	Number of successful nests	Percent success of nests
Man-made structure	1	1.4	0	0.0
Mainland hillside	6	8.3	6	100.0
Offshore islet	7	9.8	3	42.9
Ridge or connected				
sca stack	26	36.1	18	69.2
Sca stack	32	44.4	16	50.0
Total	71		43	60.6

Amchitka. With the removal of foxes by 1960, the eagles may now be readjusting to mainland nesting. (See Figs. 16 through 18.)

Production. Table 17 shows the productivity of the Amchitka eagle population. Data on fledging could not be obtained for some years because of either the lack of a helicopter at the appropriate time or because we were not on the island during the entire fledging period. Such voids are indicated in Table 17 by a question mark. A production rate of about 1.4 young per active nest and with about 60% of the nests fledging young (Table 15) places the Amchitka population among the most reproductively successful eagle populations in North America (Sprunt et al., 1973).

Nestling mortality increases as the season progresses up to the time of fledging. We have no data on the rate of mortality of young birds following fledging in late July. However, for 1972 (Fig. 19), the percentage of young lost increases faster than the percentage of total nest failure. The

nestling mortality was 20% between June 1 and July 8, whereas only 14% of the nesting attempts failed completely in that same period. This may have been a result of density dependent differential mortality of young in the nests. A comprehensive analysis of the dynamics of this eagle population has been prepared by Sherrod (1975), and earlier data were presented by White et al. (1971).

Peregrine Falcon

The Peregrine Falcon is the only other nesting raptor besides the Bald Eagle on Amchitka and is a conspicuous element of the cliff-inhabiting species

Fig. 16—Young Bald Eagles in nest surrounded by food remains. (At least three intact dead sea otter pups are in the nest along with an assortment of fish and bird remains.)

Fig. 17—Nestling Bald Eagle with a U. S. Fish and Wildlife Service band on leg.

Fig. 18—Young Bald Eagle calling at an intruder to the nest.

Table 17—Average Number of Eagle Young, 1969–1972 and 1974

Description	Year				
	1969	1970	1971	1972	1974
Number of young known in nest per nesting attempt	0.94	1.27	1.22	1.10	1.15
Number of young known in nest per nest containing young	1.54	1.78	1.73	1.53	1.72
Number of young fledged per nesting attempt	0.88?*	?	?	0.86	?
Number of young fledged per nest fledging young	1.52?*	?	?	1.42	?

*These data were gathered about 12 days prior to actual fledging and are probably too high since some mortality probably occurred during the subsequent 12 days.

(Fig. 20). In May 1968 the first in-depth study of the Peregrine Falcon in the Aleutian Islands was begun on Amchitka. Previously available data (Turner, 1886; Murie, 1959; Gabrielson and

Fig. 19—Bald Eagle nestling mortality. The range of observation dates in early June resulted from the fact that only certain parts of the island could be visited on different days owing to weather whereas in late June, when the weather improved, the entire island could be covered in one trip on one day.

Lincoln, 1959; and Kenyon, 1961) indicated only that this species is a year-round resident in the Aleutians, that it breeds on nearly all the islands, and that it frequently preys upon alcids, passerines, and ducks. A rather comprehensive analysis of the food habits of this species on Amchitka has already been given (White, Emison, and Williamson, 1973).

In June and July 1968, helicopter and ground censuses on Amchitka revealed the locations of two falcon eyries and five other locations that each had a defending pair present. Results of further studies suggest that the 1968 census did not reflect the true size of the Amchitka peregrine population. In subsequent years the number of territorial units (a unit is a pair or a defending single adult) located per year were as follows: 17 in 1969, 19 in 1970, 22 in 1971, 19 in 1972, and 16 in 1973. The year 1973 was abnormal because of early egg loss, apparently caused by weather before we arrived on the island, and some pairs had probably deserted their eyries, thereby giving a low count. The 5 years, 1969 to 1973, give an average of 18.6 pairs per year. On the basis of an estimated value of 120 miles of shoreline, the average density is one pair per 6.3 linear shoreline miles (range of 5.5 to 7.5 miles per pair).

In trying to assess the dynamics of the population, we followed each site as closely as time would permit and gathered data on the use of each site. Some of these data have been presented by White (1975). (See Figs. 21 through 25.)

Production. For the period 1970 to 1972, when data were most complete, a total of 57 nesting attempts occurred (a pair with a territory and displaying nesting behavior is considered an

Fig. 20—A Peregrine Falcon eyrie. Site is on the Pacific Ocean side in the vicinity of the Cannikin project.

Fig. 21—Clutch of Peregrine Falcon eggs. Note how the adult falcons have pulled bones of murrelets and auklets around the eggs.

Fig. 22—Banded Peregrine Falcons about half grown.

Fig. 23—Peregrine Falcon nearly ready to fledge.

attempt). Of those, 38 were successful for about 66% success. In all some 101 young were fledged in those years for an average of 33.6 young per year. Fledging success was about 2.66 young per successful nest and 1.77 young per attempted nesting. Data on sites occupied between 1968 and 1971 are summarized in Table 18. Data from peregrine populations in British Columbia (the same subspecies as that on Amchitka) suggested a fledging success of 2.36 young per successful pair between 1952 and 1958 (Beebe, 1960). Unfortunately Beebe's data do not, however, indicate what percentage of the attempts failed completely, and one must know that to say anything about net productivity. The only comparable data giving net productivity we found were from 67 pre-1942

Fig. 24—Recently fledged Peregrine Falcons.

Fig. 25—Adult male Peregrine Falcon trapped and banded in January 1973.

nesting attempts in Great Britain and New York (Hickey, 1969, p. 29). Of the 67 sites occupied, 40, or 60%, were successful for a fledging rate of 2.45 per successful pair and 1.5 per attempt. The percentage of successful nests from these two populations compares favorably with that from Amchitka.

Fledging dates on Amchitka average about June 22 with a range of June 15 to July 4. On the Queen Charlotte Islands (although farther north than Amchitka), some young apparently are flying as early as June 2 (Bechc, 1960).

DISCUSSION

As an overview of the populations of birds on Amchitka, one is impressed by several factors when this region is compared with other regions within or adjacent to the Bering Sea region. Most species on Amchitka are in some way tied to or rely on the marine ecosystem; and other ecosystems, freshwater and tundra types, are relatively less important than one might expect. This is particularly noticeable in Table 3. The interrelationship and interdependency of the marine systems of Amchitka create a high relationship score, especially when compared with that of Cape Thompson (Williamson et al., 1966). The strength of this relationship is also reflected in the numbers of marine-associated species as compared with land species.

Part of this association, however, is a function of the fact that Amchitka is an oceanic island far removed from a continental land mass from which it could derive land birds. The influence of distance is particularly noticeable when Amchitka is compared with islands such as St. Lawrence, which is about 160 km (100 miles) from both the Asian and Alaska mainlands but which has a similar summer climate to Amchitka (it is difficult, however, to separate the relative influence of distance from surface area because St. Lawrence is about ten

times as large as Amchitka). For St. Lawrence, for example, about 141 species have been recorded (Sealy et al., 1971), which is about 8% more than for Amchitka. However, 36 passerines occur on St. Lawrence, which is about 44% more than on Amchitka, and 11 breed there, which is 120% more breeding passerines. For shorebirds, 15 species occur on St. Lawrence, which is 44% less than on Amchitka, but 6 breed there, which is 50% more than on Amchitka. The greater number of both breeding passerines and shorebirds on St. Lawrence

Table 18—Summary of Data on Peregrine Falcon Eyries (1968–1971) with Remarks on Nest Success for 1971*

Eyrie location†	1968	1969	1970	1971			Remarks
				Eggs	Young	Young fledged	
1 North Bight	Adults present	Young	Young	—	3	3	
2 Constantine Harbor a	Young	Eggs, failed	—	—	—	—	Not occupied
2 Constantine Harbor b	—	—	Eggs, failed	—	—	—	Not occupied
3 Constantine Harbor c	—	—	—	4	4	4	New adult male
4 Stone Beach Cove	?	Young	Young	—	3	3	
5 C Site a	Adults present	Eggs, failed	—	—	—	—	
5 C Site b	—	—	Young	—	—	—	Not occupied
5 C Site c	—	—	—	3	3	3	Not occupied
6 Peregrine Point	Adults present	Adults present	Eggs	?	?	?	Pair present, no eyrie found
7 Chitka Cove	?	Adults present	Young	—	—	—	None seen
8 East Chapel	?	Adults present	Young	4	2	2	
9 West Chapel	?	Adults present	Adults present	—	—	—	Pair present, no eyrie found
10 Finger Point	?	Eggs	Adults present	—	2	2?	
11 Bird Cape #2	?	—	Eggs, failed	4	—	—	Eggs lost
12 Bird Cape #1	Young	Young	Young	—	—	—	Nesting started but deserted
13 Aleut Point	?	Adults present	Young	—	3	3	
14 High Cliff	?	—	—	—	—	—	Fledged young seen late June
15 Rim Point	?	—	—	—	2	2?	
16 West Column a	?	Young	—	—	—	—	None seen
16 West Column b	?	—	Young	—	—	—	None seen
17 East Column	?	Young	Young	4	4	4	
18 House Cove	?	—	—	—	2	2?	
19 Andesite Point	?	—	—	—	—	—	Lone female May–June
20 Limpet Creek a	Adults present	Young	Young	—	—	—	None seen
20 Limpet Creek	?	—	—	2	2	2	New adult female
21 Limpet–Fall Creek	?	—	—	—	3	—	Young disappeared mid-June
22 Fall Creek	?	Adults present	Adults present	—	—	—	None seen
23 Mex Island	?	Young?	Adults present	—	3	3	
24 Ultra Creek	?	Lone adult	Lone adult	—	—	—	None seen
25 Charlie Cove	Young	Eggs, failed	Eggs, failed	—	2	2	One young killed by eagle
26 Clover Lake	?	Adults present	Young	—	3	3	
27 South Bight	?	Adults present	—	—	—	—	Lone female May–June
28 Omega Point	Pair?	—	Lone adult	—	—	—	None seen

*—indicates zero, ? indicates that the number could not be determined or that eyrie not known for 1968.

†Names of the eyrie locations are reference names used in the study.

than on Amchitka appears to be principally a function of the proximity to a mainland and perhaps less so a function of land mass area.

In the comparison of Amchitka to an area smaller in size but part of the Alaskan mainland adjacent to the Bering Sea (Holms and Black, 1973), a similar disparity occurs in the passerines but even a higher percentage breed. The disparity is even further shown among shore birds where 11 nest, or 64% more species than on Amchitka.

An examination of the breeding birds on census plots, by habitat, is likewise instructive in reflecting the nature of the avifaunal composition on Amchitka. A relative comparison can be made between our census plots and those of Williamson et al. (1966) for Cape Thompson both in size and habitat occupied. Similar methods of data gathering were used in both studies.

Williamson's Cape Thompson riparian willow plot, which may be roughly compared with the Amchitka riparian meadow plot, contained 11 breeding species as opposed to 2 on Amchitka. The Cape Thompson *Carex* meadow plot had four species as compared to two on the Amchitka *Carex* meadow, and the Cape Thompson *Eriophorum* tussock plot had five breeding species as compared to two on the Amchitka *Empetrum*-*Cladonia* tundra plot. Interestingly, however, the breeding densities of Lapland Longspurs in comparable vegetation types on Amchitka and Cape Thompson are roughly similar (Williamson and Emison, 1971). Perhaps one of the more salient parameters of the breeding avifauna of Amchitka is reflected in the fact that, compared to many other arctic tundra habitats in the Bering Sea region, Amchitka shows a paucity of species but similar or even greater densities of those species present.

Geographic Affinities of Amchitka Avifauna

At the time Emison, Williamson, and White (1971) discussed the geographic and evolutionary affinities of Amchitka's avifauna, only 100 species were known from the island. Although more have been added, the general picture of affinities remains the same. Classically, the avifauna of the Bering Sea region has been analyzed in terms of its derivation from one of four faunal elements (see Fay and Cade, 1959): (1) The "Aleutican" element (species common only to the Bering Sea islands and the adjacent mainlands of Alaska and Siberia), (2) the "Panboreal" or "Circumpolar" element (essentially the same but with a much wider distribution in the northern hemisphere than the birds of the Aleutican element), (3) the "North American" element (species found on the Bering Sea islands but otherwise restricted to North

America), and (4) "Asiatic" elements (species found on the Bering Sea islands but otherwise restricted to Asia). The Aleutican and Panboreal elements are best represented in the avifauna on the Bering Sea islands. For Amchitka, about two-thirds of the species are from the Circumpolar element and the remaining ones are divided about equally between the North American and Asiatic elements.

Some interesting data emerge, however, when one reviews a group of land birds like the passerines. Of the 25 species on Amchitka, 8 are of Circumpolar distribution. These are, for this analysis, the Barn Swallow, Bank Swallow, Common Raven, Winter Wren (perhaps of the North American Element), Water Pipit, Common Redpoll, Lapland Longspur, and Snow Bunting. Twelve are of Asian affinity, the Skylark, Eye-browed Thrush, Dusky Thrush, Wheater, Siberian Rubythroat, Arctic Warbler, Gray-spotted Flycatcher, White Wagtail, Gray Wagtail, Yellow Wagtail, Brambling, and the Rustic Bunting. Only 5 are of North American affinity, the Cliff Swallow, Bohemian Waxwing [this may also be Circumpolar or Asian in Affinity (see Stegmann, 1963) and below], Gray-crowned Rosy Finch, Slate-colored Junco, and the Song Sparrow. The Asian affinity clearly has the greatest influence. However, the breeding passerines show a rather different aspect. Of the six species that either do breed or bred recently (Common Raven) on Amchitka, four are Circumpolar, the Common Raven, Winter Wren, Lapland Longspur, and Snow Bunting; the remaining two, the Song Sparrow and the Gray-crowned Rosy Finch, are of North American origin. However, if Stegmann (1963) is correct in his analysis of the origins of some of these species, i.e., the Winter Wren and the Gray-crowned Rosy Finch, then the wren should be considered as having a North American affinity and the rosy finch an Asian affinity. In any event Circumpolar species are represented by the greatest number of breeding passerines, followed then by North American forms.

The differences between the relative contributions of each continent in influencing the composition of the breeding passerines versus the migrant, accidental, and visitant passerines may be a result of two independent factors. The spring and fall storm tracks that occur during the migration months are primarily from the west (Armstrong, 1971, and Chap. 4, this volume), thus bringing Asian migrants rather than North American migrants, whereas the "stepping stone" effect of the Aleutian chain extending out from North America has had greater influence on those species which have had continuing opportunity to disperse from North America along this route and colonize

Fig. 26—Bald Eagle nest site on Pacific Ocean coast, about 3.5 km (2.2 miles) from Cannikin SZ, destroyed by Cannikin ground motion. (a) Pretest view. (b) Posttest view.

the islands. Certainly during Pleistocene interglacial periods the Aleutian chain was more closely allied to North America and in some cases even joined as a more or less contiguous string out from North America (Hopkins, 1967; Hultén, 1968).

Impact of Nuclear Tests

The reasons for gathering data on avifauna centered around the activities of underground testing on Amchitka and the impact such testing might have on the flora and fauna. It therefore seems appropriate to mention our findings here.

Predictions of possible direct effects of testing on the avifauna fell into three general categories: (1) habitat and nest-site destruction, (2) destructions of birds, and (3) accidental release of radionuclides. Recommendations were made to minimize these effects. First, tests should not be conducted during the height of the breeding season when the greatest number of birds could be affected. The breeding season for such species as the Bald Eagle, which has the longest breeding season, extends from March to August. Second, tests should be conducted during the winter months (November to February) if possible to eliminate possible transport of radionuclides by fall migrants and birds resident on Amchitka during the summer.

Actual direct effects of the Milrow and Cannikin events affected primarily the first category, habitat (Fig. 26). Using data from pretest and posttest censuses, we were unable to detect any change in population densities of species from terrestrial, freshwater lake, sea beach, or marine littoral ecosystems following Milrow. If there were long-term effects after 1970, they were masked by the impact of Cannikin.

The results of the first 2 months of post-Cannikin studies have been summarized by Kirkwood and Fuller (1972). The immediate results of the detonation were (1) the known test-related deaths of 15 birds as determined by Rausch (1973), (2) the loss of two Peregrine Falcon eyries that involved only one pair of falcons, (3) additional damage to a falcon eyrie originally damaged by Milrow, (4) the loss of six Bald Eagle nests, and (5) the damage of one eagle nest. The pair of falcons affected by the loss of two eyries is known to have used a new nest in the immediate area on the same cliff. They were successful in producing young in 1972 but not in 1973.

The complete significance of Cannikin can be fully assessed only through long-term studies. Such studies would take at least one generation time of falcons and eagles (5 to 10 years) for the effects to be detectable. Since the generation time of other bird species on Amchitka is less than that of eagles, short-term effects on these species should have time to accumulate within one generation time of eagles. The degree of damage to the avian habitat which was incurred by Cannikin argues that future detonations of such magnitude should be made only in the autumn after breeding activity has terminated and most migrants have departed.

With respect to long-term effects of Cannikin, possibly new nesting habitats for some species of small sea birds, such as auklets and petrels (not known presently to breed on Amchitka), were created by Cannikin-induced rockfalls along the Bering Sea coast. The time required for these species to invade new regions for nesting is not known. However, since there is apparently unused breeding habitat (boulder piles and hillsides)

through the Aleutians that is equally good or better than that created by Cannikin, some conditions other than availability of nesting sites may be limiting breeding. Perhaps the distribution of the food source, plankton, determines which nesting habitats will be occupied. To speculate further, we must know the distribution and abundance of plankton in the waters surrounding Amchitka, and such data are not available. Certainly, however, sites of some auklet colonies recorded in 1936 to 1938 (Murie, 1959) are now abandoned or relocated on the same island, and new colonies have been established on islands that previously had no known colonies. This suggests that, when factors necessary for successful colonization are favorable, changes in nesting colonies may nevertheless occur within a few years. Most occupied colonies are covered by a growth of vegetation, which suggests that a period of stabilization of the Cannikin-induced slides may be necessary before these slides will offer new nesting habitat.

Effects of Human Activity Associated with Tests

In addition to those direct effects of the tests described above, there were indirect effects from human activity on Amchitka. Simple cause and effect relationships between human activity and changes in avian populations are difficult to isolate because of the complex interactions and interdependencies that produced environmental change. Some examples, however, may be cited. Construction and maintenance of roads produced gravel piles and dusty borrow pits. These were effectively used by Rock Ptarmigan for observation perches and sun bathing and appeared to be beneficial to that species. Trucks passing along the roads, however, struck individuals of several species, e.g., Rock Ptarmigan, Lapland Longspurs, and Bald Eagles. Several frame buildings remaining from World War II were burned by the fire department. At least four of these buildings had been used by Gray-crowned Rosy Finches for nesting.

The total effect of AEC Amchitka Island activities on avian species may possibly never be adequately analyzed because the results of fox farming and World War II activities were not measured and because we lack data from the early part of the century as to the precise composition of the island's avifauna. Certainly a base line of data was established at the onset of AEC activities, but any changes that may occur in the long term as a function of AEC operations may be masked by the gradual changes certain to continue to occur since the removal of foxes during the 1950s as the island returns to an equilibrium condition.

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Status of the Norway Rat

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*Since the introduction of the Norway rat, *Rattus norvegicus*, to Amchitka Island, Alaska, during World War II, the species has become an established part of the island's fauna. Taxonomic identification indicates that the Norway rat is the only species of rat on the island. Population density is*

high in the beach areas and sparse inland. The environmental implications of the colonization of rats on Amchitka are difficult to determine because of the lack of base-line information before their introduction and the paucity of studies since.

The bioenvironmental studies conducted on Amchitka by the U. S. Atomic Energy Commission (AEC), Nevada Operations Office (NV), included no studies of the one species of terrestrial mammal, the Norway rat (*Rattus norvegicus* Berkenhaut), that presently inhabits the island. This chapter is an after-the-fact attempt to pull together scattered data concerning rats on Amchitka, to ascertain the most probable time of their introduction to the island, and to document their taxonomic status.

Observations of the Amchitka rat population have been scattered and desultory at best, almost always subsidiary to some more pressing interest of the investigator. Jones (1961a; 1961b) and McCann (1963) conducted small trapping studies and made observations of food habits of Amchitka rats during the summers of 1960, 1961, and 1962. Murie (1959) and Kenyon (1961; 1969) mentioned rats in connection with their effects on bird populations. Jones (1974) is also the source of some postwar pre-AEC anecdotal information. Amundsen (1974) investigated the impact on terrestrial plants of rat herbivory.

In retrospect, an ecological study of the Amchitka rats should have been a part of the multidisciplinary study in that it may have given us a better insight as to the impact of AEC activities on the island as opposed to man's overall insult (including World War II activities).

HISTORY OF RATS IN THE WESTERN ALEUTIANS AND ON AMCHITKA

Rattus norvegicus Berkenhaut, commonly known as the Norway rat, wharf rat, dock rat,

brown rat, or house rat, is an extremely recent immigrant to the western Aleutian Islands and an even more recent one to Amchitka. No remains of rats or any other terrestrial mammal have been found in any pre-contact midden excavated during archaeological investigations on Amchitka, although Desautels et al. (1970) found and identified more than 11,000 mammal bones from one site.

The first reference in the literature to rats in the Aleutians occurs in an article by Pallas (1782) (quoted in translation in Masterson and Brower, 1948). Inhabitants of Agadak Island, which is west of Amchitka, reported that rats first appeared on that island after a foreign ship had wrecked there (Masterson and Brower, 1948). (The word "Agadak" appears to be a variant of the Aleut word "Ayugadak," meaning rat.) The present name of the island, Rat Island, is a simple translation through the Russian into English and was first used by Billings and Sauer in 1802 (Orth, 1967). The island group containing Rat Island (and also Amchitka) was named the Rat Islands by Lütke in 1827 (Orth, 1967). Other western Aleutian Islands were visited by Pallas during the eighteenth century, but he does not mention rats on any of them.

Apparently there were still no rats on Amchitka during the early part of this century. A report from the Fish and Wildlife Service files concerning fox farming [Anonymous, n.d. (1936-7?)] quotes a 1920 report by a Lewis Strauss to the effect that there were no mice or squirrels on the island. Murie (1959) and Kenyon (1961; 1969) both state positively that the Norway rat was introduced to Amchitka during World War II. Murie was probably speaking from personal knowledge since he spent 1 week on the island in 1936 and 2 weeks in 1937. Kenyon (1961; personal communication) received his information

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from Murie. If there had been an early introduction, the rats either did not become established or they remained only as isolated colonies undetected by Murie.

There is no unequivocal evidence as to the exact date of introduction. R. D. Jones, Jr. (personal communication), former manager of the Aleutian Islands National Wildlife Refuge, says that when he landed on Amchitka in February 1943 as part of the military forces (the first landing had been in January) he observed no rats. Some time later he saw rats near the dock area in Constantine Harbor and subsequently noted their appearance in other parts of the island.

Schiller (1952) quotes from the Annual Sanitary Report for the Adak military sector (the sector next east of Amchitka) for the year 1944: "There are no rodents inhabiting the islands of this subsector." He further quotes from a report by Dr. Dale Jenkins, Medical Division, Army Chemical Center, concerning Adak, "The brown rat first appeared in 1946 in the dock areas and then spread to food warehouses and other buildings, and subsequently became a serious problem." Murray (1946) reports on rodent control by the U. S. Navy in Pacific Ocean areas during World War II. Officers were designated rodent control officers for particular areas, but no mention is made of needing them in the Aleutian Islands. Jones (1974) also says that the military forces on Amchitka had no organized rodent control program.

Allowing for the fact that rats are commonly overlooked, even by zoologists, until they become pests, these observations are consistent with Murie and Jones in their assertions that the Norway rat was introduced to Amchitka during World War II. Certainly only then did they become pests.

After the introduction of rats to Amchitka, we can only speculate as to their spread to the entire island as they are distributed today. One hint about their status before the AEC arrival comes from a 1960 Refuge Narrative Report (Jones, 1961a): The crew of the University of Washington's Fisheries Research Institute vessel told Jones that there were rats on one of the larger islets at the mouth of Constantine Harbor. On investigation he found that this was true. They could have reached that islet by a jetty that had been built from the mainland to the islet during the war and had washed out in a storm in 1947. In 1960 Jones saw or found signs of rats on every offshore island he visited that possessed suitable habitat, including islands that had never had connections to the shore, such as Makarius Island, Bat Island, Chapel Cove Island, and Bird Rock. Bird Rock, he said, might have received its introduction to rats from a 1943 shipwreck, but this was not true of the

others. By 1960, then, rats were firmly established on Amchitka.

Rattus norvegicus is normally a commensal species, being closely associated with areas of human habitation and use. The military had outposts and stations at many points around the periphery and in the interior of Amchitka, and at that time rats probably lived in cohabitation with man at those points, but they could not have been completely dependent on man because they have survived extended periods of his absence and are at present found around most of the edge of the island. Islands are well known for their susceptibility to invasion (Elton, 1959; MacArthur and Wilson, 1967). On an island such as Amchitka with a depauperate fauna (at the time the only other terrestrial mammal other than man present on the island was the blue fox), this adaptable species was able to find one or more ecological niches and fill them in a comparatively short time span. At present only some small beaches at the western end of the island show no sign of rats. Whether rats have not yet invaded these areas or whether they are not suitable rat habitat is unknown.

Additional introductions since the departure of the military in 1951 are probable. For instance, during the AEC occupation of Amchitka (1967 to 1973), many craft, large and small, tied up at the dock at Constantine Harbor. Ships of American registry probably did not bring rats since modern sanitary procedures aboard ships make rats no longer a problem on them. However, in August 1973 a ship of Panamanian registry tied up at the dock to take on a load of scrap metal for Taiwan, and it soon became common knowledge that there were many rats on this ship. No rats were trapped on the ship, and there was no qualified mammalogist to make observations, but these rats appeared to observers* to differ from the usual Amchitka rats. They appeared to be smaller ("half the size," one man said) and to have longer tails than the resident Amchitka rats. Since there were no rat guards on the ship's hawsers, some of the ship's rats almost surely came ashore. Having heard of these rats, I sent a message to the Site Manager asking that some be captured, and the day after the ship's departure six were caught in the dock area. All were identified as *Rattus norvegicus* by Robert S. Hoffman, University of Kansas. The number captured was too small to remove all uncertainty as to whether a nucleus population of another species (*Rattus rattus* is the only possible competitive species under the circumstances) was established.

*My principal informant was Charles Bromley, AEC Site Manager.

In any case it is doubtful that another species could be successful in competition with the established population of the Norway rat. Both Storer (1962) and Williams (1973) point out the competitive advantage the Norway rat has over other rat species in this kind of environment.

TAXONOMIC STATUS

Previous investigators have been uncertain about the species of rats on Amchitka or whether there might be more than one species present. Desautels et al. (1970) state that two species of rats were found in large numbers on Amchitka, *Rattus rattus* and *Rattus norvegicus*, but give no reference for their identification. Krog (1953) identified three rats that he collected from an eagle's nest on Amchitka as *R. norvegicus*. McCann (1963; 1974) identified the rats that he caught during the course of his 1960, 1961, and 1962 studies as *R. norvegicus*. Schiller (1952) reported that the rats on Adak were *R. norvegicus*, as confirmed by David J. Johnson of the U. S. National Museum.

Three separate collections of rats have been made from Amchitka during the past years specifically for taxonomic identification. The first appears in the acquisition log of the Museum of Natural History, University of Kansas. Five rats were collected and submitted to the museum by W. K. Clark, U. S. Fish and Wildlife Service, in May 1951. These rats were identified as *R. norvegicus*. I made the second collection in November 1972. It consisted of 10 specimens, which were submitted

to William Jackson of Bowling Green (Ohio) State University. He identified them all as *R. norvegicus*. The third collection of 8 rats was made in August 1973 by Ian Mercier, Battelle Columbus Laboratories, and submitted to the Museum of Natural History, University of Kansas, where Robert S. Hoffman identified them also as *R. norvegicus*. This series of rats bears University of Nevada at Las Vegas museum numbers, but they are on deposit at the University of Kansas.

Table 1 gives weights and measurements of these animals. Not all those mentioned in the preceding paragraph appear in this table: the 1972 shipment was delayed in transit and did not arrive in condition good enough for anything other than identification of their species.

Amundsen (1974) gives the following additional data on the weights of 82 Amchitka rats that he collected: 41 (33 female and 8 male) weighed less than 175 g, 39 (23 female and 16 male) weighed between 176 and 425 g, none were found in the 426- to 500-g range, and 2 males weighed over 500 g. McCann (1963), with a sample size of 89 rats, found that the males varied in weight from 68.6 to 420 g and females from 49.4 to 424 g. The smallest mature female in his sample weighed 158.6 g and was estimated to be about 15 weeks old and pregnant for 6 days (with the methods of Emlen and Davis, 1948).

Melanistic characteristics in the inland population on Amchitka have been observed but not in beach populations. One spotted rat was trapped from an inland population, but no albino rats have been seen on the island. Schiller (1952) notes that both spotted and albino rats occur at Adak.

Table 1—Measurements and Weights of Amchitka Rats

	Total length, mm	Tail length, mm	Hind foot, mm	Ear, mm	Weight, g	Reproductive data
Crown Reefer Point ♂ 41405*	376	182	42	21		
Crown Reefer Point ♂ 41406	420	194	42	22		
Crown Reefer Point ♀ 41407	346	156	36	20		No embryo
Crown Reefer Point ♀ 41408	349	158	37	20		No embryo
Makarius Bay ♀ 41409	435	215	45	21		15 embryos
Garbage dump ♂ 7846†	431	195	46	20	420	
Garbage dump ♂ 7847	415	77	40	21	340	
Dock area ♀ 7848	400	190	42	21	289	
Dock area ♀ 7849	365	167	39	22	185	No embryo, no scars‡
Dock area ♀ 7850	358	164	38	19	225	No embryo
Dock area ♂ 7851	330	150	38	19	187	
Dock area ♀ 7852	290	131	37	18	120	No embryo, no scars
Dock area ♂ 7853	370	171	40	20	257	

*University of Kansas Museum of Natural History number.

†University of Nevada at Las Vegas museum number.

‡No scars (no placental scars).

POPULATION AND DISTRIBUTION

Absolute numbers of wild rats are notoriously difficult to estimate, and no such estimate will be attempted here. Estimates of spatial distribution are much easier. Rat activity on Amchitka is most evident on and near beaches; on headlands and along sea cliffs, few signs (burrows, runways, or tracks) are seen except where there is a drainage of some sort leading to the beach.

In 1960 McCann trapped rats. The record is second hand (through Jones, 1961a) and seems to imply a 2% trapping success (6 rats per 300 trap nights) near ponds in the interior of the island, 3% trapping success (3 rats for 99 trap nights) on headlands, and 5.9% trapping success (71 rats for 1200 trap nights) along the beaches. In 1961 McCann (Jones, 1961b) conducted 5764 trap nights. His description of his methods is as follows: "When the beach was trapped, 100 traps were tended for three nights . . . One-third of the traps were placed at the edge of beach vegetation, one-third at the base of the headlands, and the remaining at the top of the headlands. Since the traps in one line were placed out at 25-foot intervals, the section of beach used had to be about 300 yards long. Thus, many of the smaller lengths of beach were not suitable for a trap line." McCann trapped each month from April through August, with trap successes of 2.3% on headlands (21 rats for about 930 trap nights), 7.6% on midlands (evidently "the base of headlands," 70 rats for about 930 trap nights), and 5.3% on beaches (52 rats for about 930 trap nights). Inland McCann trapped only 21 rats in 2964 trap nights (0.7% success), 18 of them around buildings. There was little change in trapping success as the season progressed. In 1962 McCann (1963) trapped 89 rats out of 1800 trap nights for a 4.9% trap success. (Sprung traps were not calculated as part of trap success.) Six hundred of these trap nights were at inland locations and produced 8 rats (1.3% success), whereas 1200 trap nights on the beaches yielded 81 rats (6.7% success).

Trap success on the beach areas of Amchitka could be greater than inland for reasons other than population density. Calhoun (1963) reported that Norway rats avoid a new object or situation in their environment. The beach-population conditioning may be such that trap avoidance, in the sense of avoiding a strange object, may not be characteristic of this population. The environment of the beach is changed at each tide, presenting a whole series of new objects. Inland rats live in a fixed environment (in the sense of new objects) and may, for that reason, be more trap shy than the beach population.

McCann (1963) said that in previous years the number of rats on the beaches had increased during the latter part of the summer (in spite of the 1961 data just quoted). In 1962 it did not appear to do so, and he supposed that younger animals may have been springing traps without getting caught. Since none of the reports indicate the number of sprung traps, we cannot judge the matter for ourselves. Our visual sightings on Amchitka do seem to substantiate an increase in numbers in the latter part of the summer; this probably indicates that Amchitka rats have a major peak in their breeding cycle in the spring and summer.

In addition to the more quantitative observations by McCann and Jones, we have two more qualitative observations from the literature. Krog (1953) noted that, although many signs of rats were seen on Amchitka during the spring (May 28 to June 17, 1952), no rats were seen. He attributed this scarcity of rats to the previous season's poisoning campaign (see Merritt, Chap. 6, this volume). Amundsen (1974) estimated that the rat population at the 1.6-ha (4-acre) Amchitka garbage dump was about 80 in the summer of 1973. During this time the garbage was buried daily in a cut-and-fill operation. This dump was closed down that fall when the island was evacuated.

HABITAT

Murie (1959) reported that the rats on Rat Island just to the east of Amchitka were "confined to the beaches in, or near, the fringe of heavy vegetation. They found a convenient refuge among the boulders on the beach and proved to be extremely wary. The interior of this island supports a very short type of vegetation, not at all suitable for cover—hence the choice of the shoreline by the rats." In addition to this possible reason, food availability probably has much to do with resident locations of rats.

Armstrong (Chap. 4, this volume) and Amundsen (Chap. 10, this volume) describe in detail the climatological and vegetational setting of Amchitka. Previous reports on the Norway rat indicate that its preferred habitat is near or along the edges of water and with man, hence the common name wharf or dock rat. At present rats on Amchitka, as previously noted, are concentrated along the beaches. Inland populations are sparse except for those areas where the rat has commingled with man, as at the main Amchitka garbage dump.

McCann attempted to determine areas used for nests. Several moss mounds had tunnel complexes in them, with one nest in each mound he tore

apart. In areas disturbed by the military, particularly along roads, he found nest sites in hummocks of the grass *Calamagrostis* sp. The entrances to rat burrows along beaches were at the base of various overhangs and storm slopes, but none of these tunnels were followed to their ends.

Generally at high tide along most beaches there is a debris line consisting of algae. The rotting algae contain the larvae of kelp flies and many marine arthropods. Rat tunnels are common in such drifts of decaying algae, but I found no nests in them. Apparently this burrowing is concerned only with feeding.

FOOD HABITS

Food availability rather than taste probably is the main factor determining the kinds of food consumed by omnivorous Norway rats. In Chap. 10 of this volume, Amundsen describes a study in which 82 rats were collected from inland areas to determine their grazing impact on terrestrial vegetation. Over 50% of these rats had over 50% by volume fresh plant material in their stomachs and over 20% had stomach contents with over 90% plant material. He found no evidence of systematic foraging and felt that the rat foraging was opportunistic and the effects on plant communities insignificant. McCann (1963) found evidence early in the season (spring) that rats were feeding on the corms of *Fritillaria camschatcensis* and several unidentified umbelliferous plants. At one nest site he found the remains of two freshly killed Aleutian sandpipers (apparently the Rock Sandpiper, *Calidris ptilocnemis*) at the entrance to the burrow. All that remained were the feathers, the tips of four wings, and three lesser leg bones. He also found a duckling on the bank of Pumphouse Lake that had been partly eaten by rats. Rats are also known to scavenge carrion on the beach, such as sea otter carcasses (Kenyon, 1969).

Many investigators have inferred that rats in abundance can be highly detrimental to colonies of nesting sea birds, although McCann (1963) felt that, especially inland, rats exert little influence on the success of nesting waterfowl. Kenyon (1961) believed that the scarcity of the Winter Wren, *Troglodytes troglodytes*, in the later 1950s was caused by rat predation. However, recent studies by Williamson and White (1974) and by White, Williamson, and Emison (Chap. 11, this volume) indicate that the Winter Wren is again abundant on the beach areas of Amchitka. As a matter of fact, wrens are commonly observed flitting in and out of rat burrows in the decaying kelp on the beach, apparently taking advantage of these burrows in their search for food.

An impact of rats on the Song Sparrow population has also been inferred. Kenyon (1961), referencing Murie's field notes, says that the Song Sparrow, *Melospiza melodia*, was common on Amchitka in 1936 and 1937. Krog (1953) makes no mention of the Song Sparrow, and Kenyon (1961) did not see a single Song Sparrow during his studies on the island. Williamson and White (1974) and White et al. (Chap. 11, this volume) estimate a present population of about 10 on the island; apparently a small population has been reestablished or was previously overlooked.

Schiller (1952) reported that the coastal rats on Adak depended largely on the invertebrate inhabitants of the littoral zone. As previously indicated, Amchitka rats frequently burrow into the rotting piles of kelp found on the beaches, and I presume that these are foraging burrows since excavation of them reveals no nests.

Cannibalism was commonly observed during trapping operations. Amundsen (1974) reports that three of his rats had their stomachs full of rat tissue and four rats had been cannibalized. During trapping operations on the beach, it was not uncommon to have rats cannibalized during the night.

As might be expected with the AEC occupation of Amchitka and a camp size up to 750 people at times, the garbage dump became a prime population center for rats. In the early part of the project, the garbage was dumped into open trenches and buried periodically. Toward the end of the project in 1973, the garbage was buried daily. Kenyon (1961) indicated that nearly 10 years after the departure of the military rats persisted in abandoned garbage dumps; however, during August 1975 I inspected the old AEC garbage dump on Amchitka and found no signs of burrows or runs.

The Norway rat functions in nature as both predator and prey. There are several published accounts of rat carcasses being found in eagle nests on Amchitka (McCann, 1963; Jones, 1961a; Murie, 1959; Krog, 1953). In one instance in my own experience an eagle removed a rat, trap and all, from the back of a pickup truck that was parked at the Amchitka main camp. Sherrod (1975) reported finding rat traps in eagle nests. Traps had to be set at dark and picked up before light to avoid disturbance by eagles.

CONTROL

From June 1967 through August 1973, during the AEC occupation of Amchitka, an active rat-control program was carried on. The rodenticide

used was Tyler's Warfarin Rat and Mouse Killer Pellets (0.025% warfarin), USDA Reg. No. 6311-9, premixed with grain or cheese. Early in 1972 peanut butter and honey were added to the mix to enhance acceptability.

Stations were located in living quarters, offices, hangars, the sewage lagoon, and the garbage dump. Traps were also set in areas used for storage, preparation, and serving of food. Additional rat controls were instigated near areas of sensitive cable runs that were susceptible to damage by gnawing. The number of traps set at these places and the success in trapping rats were not recorded.

TEST EFFECTS

Inasmuch as there was no study program directed at the Amchitka rat population, there are no quantitative data available on the effects of the nuclear tests on that population. Of the gross physical effects of the tests (Fuller and Kirkwood, Chap. 26, this volume), the subsidence around the two surface zeroes (SZ) and the formation of Cannikin Lake probably have had little effect on the rat population because of their low population density inland.

On the other hand, the extensive cliff falls and turf slides, especially along the Bering Sea coast near Cannikin SZ, almost surely destroyed some previously heavily populated stretches of beach.

ENVIRONMENTAL IMPACT

Little can be said about the impact on the Amchitka ecosystem caused by the introduction of rats since there is no base line from years before the introduction and little information since. Blue foxes, *Alopex lagopus*, introduced to Amchitka in 1921 and only extirpated in 1960, are generally believed to have eliminated the breeding population of the Aleutian Canada Goose, *Branta canadensis leucopareia*, on Amchitka and to have influenced the breeding behavior of water fowl. Kenyon (1961) believed that rats had caused the loss of two nesting species, the Winter Wren and the Song Sparrow, but these species have now returned to the island. Except for the still reduced population of Song Sparrows, the cause of which is really not known, it is difficult to identify any other possible significant impact the introduction of Norway rats has had on Amchitka ecosystems.

Rodent control around human habitation had no noticeable effects on the overall island population. Owing to their primarily nocturnal habits, in contrast with the diurnal habits of eagles, eagle

predation on Norway rats is probably a minimal influence in controlling population numbers.

The Norway rat on Amchitka has become an apparently permanent part of the island's biota.

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Limnology

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Limnological studies were conducted from 1967 to 1974 to collect and interpret data necessary for classifying the aquatic ecosystems of Amchitka Island according to their physical, chemical, and biological features. Initial surveys were followed by intensive study of lakes and streams selected for analysis of test-related effects. Pertinent limnological data were obtained from these aquatic systems to assist in the evaluation of the effects of Atomic Energy Commission operations on the surrounding environs. Investigations included physical and chemical characteristics of the waters, analysis of both phytoplankton and zooplankton communities, and rate measurements of algal photosynthesis and heterotrophic activity. The pH of the freshwaters on Amchitka ranges from acidic to alkaline, usually between 6.0 and 8.0. Alkalinities in the range of 10 to 20 mg CaCO₃/liter are common. Of the principal elements, sodium and chlorine were found at high concen-

trations, a manifestation, no doubt, of wind-carried sea spray. Phosphate was judged to be limiting algal photosynthesis in some lakes. Carbon fixation rates ranging from <1.0 to 119 mg C m⁻³ hr⁻¹ were recorded. Most of the lakes support a diverse phytoplankton composition. The most productive lakes contain large populations of Cyanophyta. Rotifers, primarily Keratella quadrata, were the dominant zooplankters and were distributed widely over the island. Copepods occurred sporadically, and cladocerans were commonly absent. Most of the lakes studied have an autochthonous supply of organic material. Heterotrophic activity was correlated to total organic-matter concentration in the lake waters. Ground shock waves had little effect on the parameters studied. The most serious perturbations resulted from the influx of drill mud to several aquatic habitats.

Limnological investigations were conducted on selected lakes, ponds, and streams of Amchitka Island from 1967 to 1974 to determine the natural characteristics of surface freshwaters and to predict and later determine the response, if any, of these aquatic ecosystems to underground nuclear testing and logistic activities associated with the execution of the tests.

Preliminary surveys were conducted on a broad areal basis to classify lakes and ponds representing various island locales. Thereafter study lakes were chosen with respect to (1) morphology and relative permanence, (2) location of surface zero (SZ) for the Milrow and Cannikin tests, (3) accessibility, (4) existence of previous sampling data, and (5) coordination of limnological sampling with the freshwater fisheries investigations. Sampling of selected streams was included as the limnology tasks expanded to encompass physicochemical characterization of lotic habitats. The principal lakes, ponds, and streams used as sampling stations are identified in Table 1 and Figs. 1 and 2.

Parameters chosen for study included water chemistry (pH, alkalinity, hardness, acidity, and concentrations of major anions, cations, and trace elements), temperature, specific conductance, dissolved solids, organic matter, zooplankton and phytoplankton populations, primary productivity

by the algal communities, and rates of heterotrophic uptake of dissolved organic material by planktonic bacteria in the lakes and ponds. The general approach was to acquire physical, chemical, and biological information (Table 2) before test time, immediately afterward (for short-term effects), and following the lapse of longer time intervals after the detonation.

METHODOLOGY

Most sampling stations were reached from the main road on foot, but, on occasion, a helicopter or Snow-Trac vehicle was used in the field work. Simple analytical procedures were performed in the laboratory provided on Amchitka Island; analyses requiring complex instrumentation were performed at the Battelle Columbus Laboratories (BCL). All water samples returned to BCL were frozen and shipped in dry ice.

Water samples were analyzed according to procedures outlined in Standard Methods (American Public Health Association, 1965; 1971). Initially, chloride-ion concentration was measured with an Orion model 401 specific-ion meter in conjunction with a solid-state chloride-ion-activity electrode. The mercuric nitrate titration method for chloride determination was eventually substituted for this procedure. Principal cations, calcium, sodium, and potassium, were analyzed by

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Table 1—Identification of Principal Study Lakes, Amchitka Island, Alaska

Lake		Map coordinates*	Drainage	Effects- study lake†
Number	Name			
1	Pumphouse Lake	585932	Pacific	M
1a	Unnamed	562927	Pacific	
2	Clevenger Lake	556945	Pacific	M
5	Jones Lake	576955	Bering	M
7	Range Pond	515965	Pacific	MC
9	Rifle Pond	516963	Pacific	MC
10	Duck Pond	515962	Pacific	MC
15	Unnamed	523976	Pacific	
18	Unnamed	528976	Pacific	
19b	Silver Salmon Lake	541990	Bering	C
23	Upper Twin Lake	518986	Pacific	M
24	Lower Twin Lake	517985	Pacific	M
25	Heart Lake	515982	Pacific	M
26	Weed Lake	527994	Bering	MC
28	Quonset Lake	519000	Bering	M
29	Long Shot Lake	512002	Bering	MC
30	Long Shot Pond	514006	Bering	MC
31b	Round Lake	521016	Bering	MC
33	Strange Pond	493030	Bering	MC
35	Mud Pond	494034	Bering	M
36	Clear Pond	493034	Bering	M
41b	Unnamed	484033	Bering	C
41c	Unnamed	481036	Bering	C
42c	Unnamed	473039	Bering	C
42d	Unnamed	471041	Bering	C
42e	Unnamed	471036	Bering	C
42f	Unnamed	467048	Bering	C
42g	Unnamed	481045	Bering	C
42h	Unnamed	472039	Bering	C
42i	Unnamed	474038	Bering	C
43a	Unnamed	465029	Bering	C
43b	Unnamed	466027	Bering	C
43c	Unnamed	465025	Bering	C
43d	Unnamed	467026	Pacific	C
43e	Unnamed	472016	Pacific	C
43f	Unnamed	461016	Pacific	C
43h	Unnamed	447018	Pacific	C
44a	Unnamed	451037	Pacific	C
44b	Unnamed	437033	Pacific	C
45	Unnamed	457054	Bering	C
46	Unnamed	453051	Bering	C
48	Unnamed	451052	Bering	C
49	Unnamed	449049	Bering	C
50a	Unnamed	445053	Bering	C
50c	Unnamed	424047	Pacific	C
51	Emerald Lake	431066	Pacific	MC
52a	Unnamed	415086	Bering	C
52c	Unnamed	396078	Pacific	C
53	Unnamed	409091	Bering	C
57	Unnamed	410100	Bering	
58a	Fault Lake	393110	Pacific	MC
58b	Unnamed	401095	Pacific	C
	Cannikin Lake	467040	Bering	
	14-Mile Lake	435063	Bering	

*Coordinates refer to approximate center of lakes (U. S. Army Corps of Engineers map of Rat Islands, Amchitka, Series Q-801).

†Lakes studied intensively to monitor detonation-related effects ascribable to Milrow (M), Cannikin (C), or both (MC).

Fig. 1—General location of principal study lakes on Amchitka Island, Alaska.

flame photometry. Later these elements were included in an evaluation of trace-element concentrations in selected lakes. Trace-element concentrations were determined by spark-source mass spectroscopy.

Water temperatures were measured with mercury thermometers. On occasion, Cannikin Lake, for example, temperature profiles were obtained with a Yellow Springs Instrument Co. (YSI) telethermometer. Specific conductance was determined with a Beckman RB3 Solu bridge. Both the unmodified Winkler technique and a YSI D. O. meter were used to measure levels of dissolved oxygen.

Plankton was sampled with a standard Wisconsin net having a No. 20 silk bolting cloth cone and bucket. Horizontal and sometimes vertical tows (Cannikin Lake) were made for qualitative estimation of organismal diversity. Ten-liter quantitative samples were collected with either a Van Dorn or a Kemmerer water sampler. After concentration of the samples, zooplankton were counted in a Sedgwick-Rafter cell at 100x. Phytoplankton genera were identified at 450x. Partial samplings of small nanoplankton organisms

were obtained by filtering raw lake water through a 13-mm-diameter Millipore filter with a 0.45- μ m pore size. After these filters had been cleared with immersion oil, permanent slides of the filters were made. All slides were examined at 1000x with phase-contrast microscopy. Compilation of a complete list of plankton species was not included among the program objectives.

Primary-productivity measurements were conducted both in situ and in the laboratory with the Steemann Nielsen ^{14}C uptake technique described by Strickland and Parsons (1965). Field incubations were made at midday for a duration of 4 hr. Laboratory incubations were made with an illuminated incubator held at constant temperature (within $\pm 1^\circ\text{C}$ of the prevailing lake temperature) and light intensity (200 ft-c). Glass reagent bottles of 125-ml volume served as the light and dark (enclosed in black polyethylene bags) productivity bottles. These were filled with lake water, spiked with 10 μCi of labeled NaHCO_3 , incubated, and fixed by the addition of Formalin to terminate incorporation of the carbon tag by the phytoplankton. A 25-ml portion from each incubation bottle was vacuum filtered through HA Millipore

Fig. 2—General location of streams sampled on Amchitka Island.

filters (25-mm-diameter, 0.45- μ m pore size) at a pressure not exceeding 15 in. Hg. Filters were dried, placed in scintillation vials, and dissolved with methylcellosolve. The scintillation cocktail consisted of PPO (2,5 diphenyloxazole), naphthalene, and dioxane. Before radioassay, Cab-O-Sil thixotropic gel was added to each vial to prevent the particulate planktonic organisms from settling out. Each sample was counted until the 1% confidence level was reached.

The magnitude of heterotrophic activity by the bacteria populations was estimated by measuring the kinetics of uptake of $2\text{-}^{14}\text{C}$ -labeled sodium acetate (Wright and Hobbie, 1966). The Lineweaver-Burk modification of the Michaelis-Menten equation was used to estimate the following parameters: V_t , the theoretical maximum rate of uptake of the organic substrate tested; T_t , the turnover time for use of the substrate; and $K_t + S_n$, the upper limit for natural substrate concentration. The V_t is a useful spot indicator of unusual organic enrichment since it is directly related to the activity and size of the bacteria population.

RESULTS AND DISCUSSION

General

The freshwater habitats of Amchitka Island include a few rapidly flowing streams, numerous small seasonal rivulets, a few cirque lakes, and several thousand shallow lakes and ponds. Some of the larger lakes are situated in fault zones; maximum water depths (from 3 to 5 m) occur in such lakes. The majority of lakes and ponds are small (less than 1 ha in area) and less than 1 m in depth. These water bodies are distributed throughout the southeastern two-thirds of the island. Many of the ponds and lakes are of the seepage type, receiving surface runoff from the surrounding region, and have no definite inlet or outlet. Most of the larger lakes on the island have well-formed outlets, but water flow through them may be seasonal. Field observations suggest that some of the lakes that have turf banks covered with tundra vegetation are slowly increasing in surface area. This process results from bank erosion due to extensive wave action during much of the year.

Table 2—Summary of Attributes Determined Since Initiation of the Limnology Studies in 1967

	Fall 1969						Fall 1971							
	Fall 1967	Spring 1968	Fall 1968	Spring 1969	Pre-Milrow	Post-Milrow	Spring 1970	Fall 1970	Spring 1971	Pre-Cannikin	Post-Cannikin	Spring 1972	Fall 1972	Spring 1973
pH	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Alkalinity	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Temperature	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Conductivity								X	X	X	X	X	X	X
Chloride										X		X	X	X
Hardness												X	X	X
Trace elements	X	X										X	X	X
Solids												X	X	
Suspended sediment					X	X	X							
Organic matter			X	X			X	X	X	X	X	X		
Heterotrophy			X	X			X							
Primary productivity	X	X	X	X			X		X	X	X	X	X	X
Phytoplankton (quant.)	X	X					X							
Phytoplankton (qual.)	X	X	X	X	X	X	X					X		X
Zooplankton (quant.)	X	X			X	X	X	X				X	X	X
Zooplankton (qual.)	X	X	X	X	X	X	X	X				X	X	X
Acidity													X	

The bottom composition of the lakes and ponds ranges from compacted peat and organic detritus to rock embedded in fine clays. Many of the shallower bodies of water support rich populations of rooted aquatic plants and associated periphyton communities. *Hippurus vulgaris*, *Myriophyllum* sp., and *Ranunculus* sp. form extensive beds in some lakes. Others contain no populations of rooted tracheophytes. Dry lake beds with various stages of revegetation by terrestrial species can be found throughout the southeastern two-thirds of the island.

An important environmental feature of Amchitka Island is the prevalence of relatively strong winds. These winds are extremely important to the physical and chemical characteristics of the aquatic ecosystems. Water and air temperatures are usually nearly equilibrated; a differential exceeding 2°C rarely exists. Constant turbulence results in orthograde oxygen saturation in lake waters during the ice-free portion of the year. Freeze-over during winter is intermittent, and periods of ice cover are of short duration. Lake water was saturated with oxygen even during periods of ice cover (Koob,

1968); therefore winter kill of organisms due to oxygen depletion is unlikely to occur.

The recently formed Cannikin Lake, with a surface area of approximately 12 ha (30 acres) and a maximum depth of 9.5 m (31 ft) (Gonzalez, Wollitz, and Brethauer, 1974), is the largest lake on Amchitka Island in terms of volume. This lake partially filled the subsidence crater that formed after the Cannikin detonation, Nov. 6, 1971, and reached maximum volume during late autumn 1972. The lake is fed by surface runoff and has an outlet, White Alice Creek, to the Bering Sea. Its bottom consists of submerged crowberry meadow, typical of the area in which the subsidence crater formed. Cannikin Lake has the distinction of being the only freshwater lake in the world formed by a contained underground nuclear detonation.

Inorganic Chemistry

Chemical data obtained from the lakes, ponds, and streams sampled indicate that chemical character is quite varied among such freshwaters on Amchitka Island (Table 3). Factors probably re-

Table 3—Chemistry of Some Lakes and Streams on Amchitka Island*

	pH	Alkalinity, mg CaCO ₃ / liter	Total hardness, mg/liter	Specific conductance, μmhos/cm (at 25 °C)	Chloride, mg/liter
LAKES					
1	7.89(20)	56.4(19)	8.0(2)	328(10)	44.1(4)
1a	8.92(3)	38.8(3)	28.7(3)	302(3)	52.7(3)
2	8.04(18)	51.3(18)	24.5(4)	284(10)	40.0(5)
5	8.17(19)	70.2(19)	15.0(3)	370(11)	45.2(4)
7	5.70(12)	<1.0(12)	21.0(2)	210(5)	57.4(3)
9	6.29(25)	2.3(25)	27.2(3)	248(14)	49.0(6)
10	6.71(24)	5.9(24)	42.7(3)	377(14)	88.3(6)
19b	7.69(5)	36.8(5)	27.3(2)	221(5)	38.6(4)
23	7.03(5)	9.0(6)	14.0(1)	155(5)	26.5(1)
24	6.94(3)	8.5(4)		175(3)	
25	7.01(3)	7.6(4)		153(3)	
26	7.31(29)	20.4(29)	24.7(5)	182(12)	31.9(6)
28	7.36(21)	25.6(21)	21.9(4)	197(10)	34.0(6)
29	7.17(22)	12.9(23)	19.4(4)	159(12)	35.2(6)
30	5.90(22)	1.0(22)	13.8(3)	143(12)	33.6(6)
31b	7.18(25)	17.7(24)	21.8(4)	194(16)	33.9(7)
33	7.03(19)	10.2(19)	24.0(2)	149(10)	33.9(5)
35	5.59(15)	<1.0(15)	8.5(2)	158(6)	32.8(2)
36	5.58(15)	<1.0(15)	10.3(2)	162(5)	34.8(2)
41b	6.13(10)	1.2(10)	9.3(2)	120(10)	25.3(6)
41c	6.55(4)	6.5(4)		117(4)	26.6(3)
42c	6.04(8)	1.09(8)		115(7)	25.7(3)
42d	7.40(9)	31.7(9)		198(8)	31.5(4)
42e	6.23(8)	3.3(8)		124(7)	22.8(3)
42f	5.49(12)	<1.0(12)	10.3(2)	122(11)	25.8(5)
42g	7.32(9)	24.0(9)	27.0(2)	202(9)	38.4(6)
42h	5.55(3)	<1.0(3)		108(3)	24.3(3)
42i	5.76(3)	<1.0(3)		107(3)	23.7(2)
43a	6.58(4)	7.7(4)		146(4)	7.0(4)
43b	5.90(17)	<1.0(17)	12.0(4)	124(16)	27.6(9)
43c	6.90(16)	9.8(16)	24.0(4)	155(15)	29.8(8)
43d	5.84(4)	<1.0(4)	11.0(4)	128(4)	29.2(4)
43e	7.03(6)	7.0(5)	21.5(2)	168(6)	31.4(4)
43f	7.26(6)	13.2(5)	28.5(3)	184(6)	36.9(4)
43h	7.29(6)	16.2(6)	28.5(2)	237(6)	49.8(4)
44a	6.84(11)	11.6(11)	20.5(2)	162(11)	30.9(6)
44b	7.43(6)	26.6(6)	35.8(2)	229(6)	40.0(4)
45	7.15(9)	14.5(9)	16.0(2)	163(9)	34.9(5)
46	6.92(2)	18.6(2)		170(2)	34.0(2)
48	6.41(2)	9.4(2)		120(2)	25.5(2)
49	6.31(12)	2.2(12)	10.8	118(12)	26.1(7)
50a	7.07(12)	14.7(12)	23.4(4)	156(12)	30.3(8)
50c	7.52(6)	31.9(6)	33.0(2)	238(6)	39.0(4)
51	6.87(14)	9.6(14)	17.2(4)	165(8)	34.0(5)
52a	6.79(8)	6.4(8)	17.0(2)	142(8)	28.1(4)
52c	7.10(1)	22.5(1)		195(1)	37.2(1)
53	6.69(8)	3.9(8)	8.4(2)	135(8)	29.6(4)
58a	6.69(11)	4.9(11)	12.8(3)	138(10)	31.7(5)
58b	6.52(14)	2.9(14)		150(7)	
Cannikin Lake	7.74(3)	55.2(3)	32.3(3)	472(3)	72.1(3)
STREAMS					
Roller Coaster Cr.	7.61(1)	36.1(1)	20.8(1)	210(1)	32.5(1)
Bridge Cr.	7.29(4)	33.3(4)	29.0(3)	210(4)	34.9(3)
Clevenger Cr.	7.60(5)	96.1(5)	29.5(4)	444(4)	53.0(4)

Table 3—(Continued)

	pH	Alkalinity, mg CaCO ₃ / liter	Total hardness, mg/liter	Specific conductance, μmhos/cm (at 25°C)	Chloride, mg/liter
Duck Cove Cr.	7.39(3)	31.2(3)	27.5(2)	229(3)	40.5(2)
C-Site Area					
Cr.-S	7.22(3)	30.7(3)	27.3(2)	194(2)	33.9(2)
C-Site Area					
Cr.-W	6.94(2)	42.2(3)	34.0(2)	218(3)	32.4(2)
Ultra Cr.	7.93(1)	48.2(1)	35.0(1)	230(1)	35.5(1)
Falls Cr.	7.52(5)	42.9(4)	33.8(4)	242(5)	37.1(4)
Fumarole Cove Cr.	7.95(1)	30.9(1)	42.0(1)	205(1)	32.0(1)
Chapel Cove Cr.	7.54(1)	19.6(1)	24.0(1)	140(1)	24.0(1)
Top Side Cr.	7.60(1)	21.4(1)	25.0(1)	160(1)	27.5(1)
Midden Cove Cr.	7.48(1)	14.3(1)	23.0(1)	150(1)	24.0(1)
Signal Cove Cr.	7.45(1)	14.9(1)	24.0(1)	160(1)	34.0(1)
Burr House Cove					
Cr.-N	7.52(1)	22.5(1)	27.0(1)	160(1)	26.5(1)
Burr House Cove					
Cr.-S	7.39(1)	21.6(1)	28.0(1)	170(1)	26.5(1)

*Numbers in parentheses are the number of measurements made throughout the study period, 1967 to 1974.

sponsible are soil and vegetation composition in the respective drainage basins and proximity to wind-carried ocean spray.

Values for pH in the small pools and shallow lakes range between 5.0 and 6.5. In large lakes and in lakes and ponds in areas disturbed by road construction, pH values from 6.0 to 9.5 were recorded. The highest average pH values occurred in lakes 1, 1a, 2, and 5, probably owing to increases in pH brought about by photosynthetic activity of the relatively abundant algal populations occurring there. The pH is fairly uniform among the streams sampled; with one exception values were between 7 and 8. In streams pH is probably not subjected to the influence of the photosynthetic activity that occurs in lakes and ponds.

Generally, Amchitka's freshwater systems possess low buffering capacity. The lakes and ponds are strictly bicarbonate waters (Beetem et al., 1971). Alkalinity values in the range of 10 to 20 mg CaCO₃/liter were common. Some lakes and ponds have alkalinity values of 1 mg or less, whereas others have values above 50 mg CaCO₃/liter. The variation in alkalinity among streams is distinct, unlike that observed for pH. Alkalinity is influenced by the drainage basin, particularly in those portions of the island where human activity occurs. On Amchitka, windblown dust and drainage water enriched with inorganic material arising from construction activities increased alkalinity 10-fold in affected ponds. Lake 5 consistently

possessed a high buffering capacity, approximately 70 mg CaCO₃/liter. This lake lies in the Constantine Harbor graben, an area underlain with mineral soils of glacial and interglacial origin (Everett, 1971). Lakes 1 and 2 are also high-alkalinity waters. These lakes are surrounded by soil associations of relatively high mineral content. Cannikin Lake owes its high buffering capacity to (1) input of runoff water from adjacent gravel test pads and roads and (2) solubilization of inundated drill-mud materials.

Total hardness determinations commenced during the spring of 1972. The total hardness of water is attributed to cations of calcium, magnesium, aluminum, iron, manganese, strontium, and zinc. However, except for calcium and magnesium, the concentration of these cations is usually insignificant in natural waters. Hardness therefore has been defined as a characteristic of water which represents the total concentration of calcium and magnesium (American Public Health Association, 1971). The amount of hardness that is equivalent to the total alkalinity is termed carbonate hardness, and the amount of hardness in excess of this is designated noncarbonate hardness. Of the 37 lakes for which hardness data are given in Table 3, 7 have carbonate hardness and 30 have noncarbonate hardness. Values for total hardness in the lentic habitats ranged from 8 to 43 mg/liter (as CaCO₃). Most values fell within the range of 15 to 30 mg/liter. A noticeable difference exists between the highland streams in the northwest portion of

the island and the lowland streams in the southeast portion: The highland streams possess non-carbonate hardness; the lowland streams possess carbonate hardness. This indicates that in the lowland streams the calcium-magnesium concentrations (expressed as milligrams of CaCO_3 per liter) do not exceed the total alkalinity values (expressed as milligrams of CaCO_3 per liter). Whether or not this difference is due to a relationship between the speed of the current and mineral solubilization is unknown. Too, perhaps the difference is due to regional soils composition of these areas, although this contention cannot be solidly reconciled from the soil maps in the pocket at the back of this volume.

Chloride-ion concentration is definitely linked to the proximity of the water body to either the Pacific Ocean or the Bering Sea. Of the lakes sampled, lake 10 has the highest average chloride content. This lake lies very close (approximately 30 m, see Fig. 1) to the sea. Actually salt-laden sea spray reaches most of the lakes on Amchitka, but it reaches lakes bordering the sea much more frequently. Chloride-ion concentrations for Amchitka lakes fall in the range of freshwaters designated as chloride waters by Hutchinson (1957).

Average specific conductance ranged from 107 $\mu\text{mhos/cm}$ in lake 42i to 472 $\mu\text{mhos/cm}$ in Cannikin Lake. Values for Cannikin Lake and Clevenger Creek (Table 3) do not represent purely natural conditions. During these investigations both systems had inputs of drill mud, which increased dissolved-solids concentration and, concomitantly, specific conductance. Recent measurements (Burkett, 1974) indicate a reduction in specific conductance in both Cannikin Lake and Clevenger Creek.

During the spring of 1972, five lakes (5, 7, 29, 30, and 31b) were analyzed for total, nonfiltrable, and filtrable residues to provide data for evaluating the relation between dissolved solids and specific

conductance in Amchitka lakes (Table 4). The five lakes selected for this analysis are representative of the various lake types found on the island. Lakes 7 and 30 are acidic brown-water lakes with very low alkalinity, whereas lakes 29 and 31b are near neutral in pH and have alkalinities between 10 and 20 mg CaCO_3 /liter. Lake 5 is alkaline; the pH is usually between 8.0 and 9.5, and the alkalinity ranges between 50 and 90 mg CaCO_3 /liter.

There was no apparent relationship in these samples between either pH or alkalinity and total, suspended, or dissolved solids (Birch, 1973). There is, of course, an inherent relationship between the dissolved-ion content of water and its capacity for conducting an electric current which is measured by specific conductance. An empirical factor can be used to estimate dissolved-ion content from specific conductance by multiplication. Standard Methods (American Public Health Association, 1971) indicates that the factor may vary between 0.55 and 0.90. In Table 4 these factors vary from 0.50 to 0.71 and average 0.59.

Calcium, sodium, and potassium concentrations were determined by flame photometry during the initial phases (1967 and 1968) of the research. Table 5 lists cationic concentrations in some of the lakes that eventually became intensive-study lakes. One relationship apparent from these data is that the order of cationic concentrations is usually sodium > calcium > potassium. The influence of wind-carried ocean spray is again apparent; in most freshwaters of the world, the calcium ion is more abundant than the sodium ion. Lake 10 has the highest sodium levels, and this corresponded with the high chloride levels found in this lake (Table 3). Calcium levels were low in all lakes sampled, and little variation in calcium content existed between lakes. These observations are probably related to the igneous lithology of Amchitka Island. Potassium levels are in the range reported for many other freshwater lakes (Hutchinson, 1957). Whether or not ion-poor water from

Table 4—Residue (Solids) Analyses* from Selected Stations During Spring 1972

Lake	Total residue (total solids), mg/liter	Nonfiltrable residue (suspended solids), mg/liter	Filtrable residue (dissolved solids), mg/liter	Specific conductance, $\mu\text{mhos/cm}$ (at 25°C)	Ratio of dissolved solids to specific conductivity
Acidic					
7	200.2	8.3	192.0	270	0.71
30	121.1	20.2	100.9	175	0.58
Neutral					
29	118.9	3.8	115.1	200	0.57
31b	141.0	11.4	129.4	260	0.50
Alkaline					
5	222.2	19.5	202.8	338	0.60

*Samples dried at 103 to 105°C; Millipore filter pore size, 0.45 μm .

Table 5—Calcium, Sodium, and Potassium in Amchitka Lakes, Autumn 1967 and Spring 1968

Lake	Season	Concentration, mg/liter		
		Ca ²⁺	Na ⁺	K ⁺
1	Spring	1.3	36	2.5
2	Autumn	2.2	38	2.6
	Autumn	1.4	17	1.2
	Spring	1.3	21	1.2
5	Autumn	1.5	20	0.9
	Spring	1.8	48	1.9
7	Autumn	1.7	26	1.2
	Spring	1.6	21	1.1
9	Autumn	2.1	21	1.2
	Autumn	1.8	34	1.7
	Spring	1.1	16	1.0
10	Autumn	1.9	51	3.4
23	Autumn	1.2	15	0.7
26	Autumn		10	0.5
	Spring	1.4	17	0.5
	Spring	2.1	33	1.2
	Spring	3.3	33	1.2
	Spring	3.0	31	1.0
28	Autumn	2.8	31	1.6
	Autumn	3.4	31	1.6
	Spring	2.8	18	1.3
29	Autumn	2.5	20	1.3
	Spring	1.6	10	0.6
30	Autumn	1.8	26	0.9
31b	Spring	2.2	28	1.3
	Spring	2.6	21	1.2
33	Autumn	0.6	5	0.3
	Autumn	1.4		0.8
	Spring	0.3	4	0.2
35	Autumn	0.9	15	0.6
	Autumn	0.5	11	0.6
	Autumn	0.4	6	0.2
36	Autumn	0.6	15	0.8
	Autumn	1.4	18	0.5
	Autumn	1.4	23	0.6
48	Autumn	1.0	8	0.8
49	Autumn	1.4	21	0.8
50a	Autumn	1.4	9	0.8
51	Autumn	1.7	10	1.0
58a	Spring	0.9	14	0.6
	Spring	1.0	12	0.7

snow melt during springtime has a dilution effect on cationic concentration cannot be ascertained from these data (Table 5). Slight differences in the concentration of these cations between autumn and spring are apparent; however, it is doubtful that these variations are significant.

The molybdc acid–ascorbic acid–antimony method described by Strickland and Parsons (1965) was used to determine the orthophosphate (PO₄–P) concentration in samples. No orthophosphate was detected in lakes 7, 9, 26, 30, and 33. Orthophosphate was found in lakes 28, 5, 2, and 1 and in water from the spring supplying water to lake 2 and to the entire AEC camp (Table 6). In

a second, more-extensive sampling of lakes 1 and 2, high concentrations of PO₄–P were found in the inlet waters of both lakes. The source of this dissolved PO₄–P is unknown. Surface drainage from previous military encampments and from the AEC camp area is a possibility. Water samples were taken from regions surrounding both areas. High PO₄–P concentrations were present in water

Table 6—Concentration of PO₄–P in Various Water Sources

Water source	Concentration, mg P/liter
Lake 1	0.94
Lake 2	0.14
Lake 5	0.05
Lake 28	0.02
Spring water	0.95
Tap water	0.92

bodies situated in the southeast portion of the island in the vicinity of lake 1. This area is marked with a fault line, and springs arising along this fault are the most probable source of water rich in PO₄–P. An underground source of the PO₄–P entering lake 2 was discovered. Water from the spring flowing into this lake contained over 1 mg PO₄–P/liter; surface-drainage water both from an adjacent hillside and from the old military camp area contained a PO₄–P concentration of 0.02 mg/liter. That the springs supplying water to lakes 1 and 2 do not derive their source of PO₄–P from present human occupation can be deduced from a comparison of current PO₄–P values with earlier data (Beetem et al., 1971) obtained before the establishment of the AEC camp complex. The values for lake 2 are nearly identical (0.94 mg/liter at present vs. 0.99 mg/liter in 1965), indicating a long-term relatively constant supply of PO₄–P to these underground waters. Whether this phosphate source can be attributed to organic pollution from the World War II occupation or to an earlier geological inorganic source is not known.

Element Analysis

Mass-spectrographic element analysis was conducted on water samples from eight Amchitka lakes (Table 7). Although the mass-spectrographic technique for water analysis has good precision, it lacks high accuracy; therefore these data can be used for comparisons between lakes, but their interpretation as absolute values must be approached with caution. Lakes 5, 10, 29, 30, 31b, 45, and 58a and Cannikin Lake differ considerably in their physical, chemical, and biological charac-

Table 7—Mass-Spectrographic Analysis of Lake-Water Samples

Element	Concentration of element, ppb by weight								
	Lake							Cannikin	
	5	29	30	31b	58a	45	10	Surface	Bottom
Li	1	1	1	1	1	1	0.6	0.1	0.06
Be	0.6	0.2	0.1	0.1	<0.005	<0.002	<0.003	<0.006	<0.006
B	30	20	10	10	10	4	10	60	60
F	30	15	6	6	50	20	30	60	30
Na	*	*	*	*	*	*	*	*	*
Mg	2,000	~5,000†	1,000	~5,000	~10,000	~3,000	~10,000	1,000	1,000
Al	5	30	30	10	500	1,000	50	60	100
Si	300	300	60	400	1,000	~10,000	300	1,500	6,000
P	10	10	6	10	5	30	6	10	10
S	1,000	1,500	1,000	600	1,000	2,000	1,500	1,000	3,000
Cl	*	*	*	*	*	*	*	*	*
K	~5,000	~5,000	~1,000	~1,000	~2,000	~5,000	~3,000	3,000	3,000
Ca	500	~10,000	~2,000	~1,000	~2,000	~5,000	~3,000	1,000	1,000
Sc	<0.3	<0.3	<0.2	<0.2	<0.2	<0.6	<3	<0.6	<0.6
Ti	<2	<2	<1	<1	3	30	<20	10	30
V	1	0.6	1	1	0.5	6	3	10	50
Cr	1	1	<0.6	<0.6	1	1	1	<2	<2
Mn	10	10	30	6	15	6	20	10	50
Fe	15	15	10	30	25	1,000	50	200	600
Co	<0.6	0.6	0.4	0.4	<3	<1	<2	<2	<2
Ni	<0.6	1	0.6	0.4	<2	≤3	<1	<2	<5
Cu	100	500	150	300	3	2	<10	<2	<5
Zn	<3	10	20	10	≤2	6	≤5	<10	<10
Ga	<0.2	<0.2	<0.1	<0.1	<0.4	<0.4	<6	<1	<1
Ge	<0.1	<0.1	<0.1	<0.1	<2	<1	<3	3	3
As	1	1	1	1	≤0.5	<2	≤3	3	10
Se	<2	<2	<2	<2	<1	<1	<3	<3	<3
Br	100	100	100	50	400	400	600	30	60
Rb	2	5	1	3	2	10	10	1	3
Sr	5	50	20	20	20	100	100	3	6
Y	<0.2	<0.2	<0.1	<0.1	<1	<0.4	<0.6	<0.2	<0.3
Zr	<0.3	<1	<1	<0.2	<0.6	<0.6	<0.6	<0.3	<0.3
Nb	<0.2	<0.2	<0.1	<0.1	<0.3	<0.1	<0.2	<0.5	<0.5
Mo	≤0.6	≤1	≤1	≤0.4	<2	<2	<3	0.6	0.6
Rh	<0.2	<0.1	<0.1	<0.1	<0.2	<0.1	<0.2	<0.2	<0.2
Pd	<0.3	<0.6	<0.4	<0.2	<0.3	<0.1	<0.2	<0.3	<0.3
Ag	0.3	1	2	0.4	<0.2	<0.1	<0.1	<0.1	<0.3
Cd	≤0.1	0.6	0.4	≤0.1	<0.3	≤0.4	≤0.6	<0.2	<0.2
In	<0.2	<0.2	<0.1	<0.1	<0.3	<0.1	<0.6	<0.2	<0.2
Sn	≤0.6	1	1	≤0.2	<1	<0.4	<0.6	<0.3	<0.2
Sb	<0.3	<0.3	<0.2	<0.2	<0.5	<0.2	<1	<0.6	<0.6
Te	<0.1	<0.1	<0.06	<0.06	<0.2	<0.06	<0.2	<0.3	<0.6
I	2	5	4	4	10	1	10	2	4
Ru	<1	<0.3	<0.4	<0.4	<0.3	<1	<2	<0.6	<1
Cs	<0.2	<0.2	<0.1	<0.1	<0.5	<0.2	<1	<0.3	<0.6
Ba	0.6	2	1	1	7	7	3	0.3	1
La	<0.2	<0.2	<0.1	<0.1	<0.5	<0.2	<0.3	<1	<1
Ce	<0.3	<0.3	<0.2	<0.2	<0.5	<0.2	<0.3	<0.1	<0.1
Pr	<0.2	<0.2	<0.1	<0.1	<0.1	<0.06	<0.1	<0.3	<0.3
Nd	<0.1	<0.1	<0.06	<0.06	<0.5	<0.2	<0.3	<0.2	<0.2
Sm	<0.1	<0.1	<0.06	<0.06	<0.1	<0.06	<0.1	<0.1	<0.1
Eu	<0.06	<0.06	<0.04	<0.04	<0.03	<0.2	<0.3	<0.2	<0.2
Gd	<0.1	<0.1	<0.06	<0.06	<0.1	<0.04	<0.06	<0.1	<0.1
Tb	<0.3	<0.3	<0.2	<0.2	<0.1	<0.2	<0.3	<0.3	<0.3
Dy	<0.1	<0.1	<0.06	<0.06	<0.1	<0.1	<0.1	<0.2	<0.2
Ho	<0.3	<0.1	<0.06	<0.06	<0.1	<2	<0.3	<0.3	<0.3
Er	<0.1	<0.1	<0.06	<0.06	<0.1	<0.1	<0.2	<0.3	<0.3
Tm	<0.03	<0.03	<0.2	<0.02	<0.5	<0.06	<0.06	<0.1	<0.1
Yb	<0.1	<0.1	<0.06	<0.06	<0.4	<0.4	<0.6	<0.1	<0.1
Lu	<0.1	<0.1	<0.04	<0.1	<0.5	<0.2	<0.3	<0.2	<0.2

Table 7—(Continued)

Element	Concentration of element, ppb by weight							Cannikin	
	Lake							Surface	Bottom
	5	29	30	31b	58a	45	10		
Hf	<0.1	<0.1	<0.06	<0.06	<0.2	<0.06	<0.3	<0.1	<0.1
Ta	<2	<3	<2	<1	<50†	<2	<6	<0.6	<0.6
W	<0.1	<0.1	<0.06	<0.06	<0.1	<0.1	<0.1	<0.1	<0.1
Re	<0.06	<0.06	<0.04	<0.04	<0.1	<0.2	<0.3	<0.3	<0.6
Os	<0.1	<0.1	<0.06	<0.06	<0.4	<0.4	<0.4	<0.1	<0.1
Ir	<0.06	<0.1	<0.1	<0.1	<0.4	<1	<2	<0.2	<0.2
Pt	<0.1	<0.1	<0.06	<0.06	<0.2	<0.2	<0.2	<0.1	<0.1
Au	<0.3	<0.3	<0.2	<0.2	<0.5	<0.2	<0.3	<0.3	<0.3
Hg	<0.1	<0.1	<0.1	<0.1	<0.2	<0.2	<0.2	<0.3	<0.3
Tl	<0.06	<0.06	<0.06	<0.06	<0.1	<0.1	<0.1	<0.3	<0.3
Pb	0.2	0.6	0.6	0.6	2	0.4	0.2	<0.3	<0.3
Bi	<0.03	<0.03	<0.02	<0.02	<0.04	<0.04	<0.04	<0.1	<0.1
Th	<0.03	<0.03	<0.02	<0.02	<0.05	0.5	0.5	<0.06	<0.06
U	<0.03	0.1	0.1	<0.02	<0.1	0.5	0.5	<0.06	<0.06

*Approximately 100,000 ppb.

†Approximation of concentration that exceeded the upper limit of detectability.

‡Contamination from tantalum electrode holders.

teristics. Element analysis is of particular importance in the study of aquatic ecosystems because certain elements constitute nutrients essential to algal metabolism. According to Nicholas (1963), 16 elements are needed for the growth of various algal species: N, P, Ca, Mg, Na, K, S, Fe, Mn, Cu, Zn, Mo, B, Cl, Co, and V.

In none of the lakes sampled were any of the above elements absent; Ca, K, Cl, Na, and Mg were present at high levels (exceeding the upper detection limits of mass-spectrographic analysis). Iron concentrations ranged from 10 to 1000 ppb. That iron concentration in Cannikin Lake was greater at the bottom might reflect a microzonal oxygen deficit near the bottom. Manganese was recorded at concentrations varying from 6 to 50 ppb. The concentration of boron was lowest in lake 45 (4 ppb) and highest in Cannikin Lake (60 ppb). Lakes 5, 29, 30, and 31b had relatively high copper concentrations; Cannikin Lake and lakes 58a, 45, and 10 contained the element at levels less than 10 ppb. With few exceptions, Zn, P, Mo, Co, and V occurred at levels less than 10 ppb in all lakes.

In freshwater lakes the sulfate ion is usually the second or third most abundant anion, exceeded only by bicarbonate and occasionally by silicate (Hutchinson, 1957). However, because of the wind-carried sea spray discussed earlier, chlorine exceeded sulfur in all the lakes examined and exceeded silicon in five lakes. Sulfur levels were greater than those recorded for silicon in lakes 5, 10, 29, 30, and 31b. Both sulfur and silicon concentrations were markedly higher in the bottom waters of Cannikin Lake than in the surface waters.

These elements follow a depth distribution determined by their source, in this instance probably exposed bedrock materials at the lake bottom. Specifically, silicon is derived from decomposition of aluminosilicate minerals. Aluminum also occurred at greater concentrations in the bottom waters of Cannikin Lake. Sulfur in surface waters commonly originates from rainwater and sedimentary rock bearing calcium sulfate. Probably neither source is very applicable to Amchitka owing to the remoteness of the island from industrial activity and to the lack of sulfate-bearing rocks. Here sea spray would be an important source of sulfur.

The quantity of manganese present in the surface waters of the earth is generally less than the quantity of iron. Note, however, that in lake 30 manganese concentration exceeded that for iron. The ratio of iron to manganese in surface waters is normally well below the geochemical ratio of 50 : 1. An anomalous condition was observed in lake 45, where the ratio was 167 : 1. Excluding the above rarities, the ratios of iron to manganese in the lakes sampled were equal to or considerably below 10 : 1.

Concentrations of copper did not follow any discernable pattern with regard to hardness of lake water. In hard water copper is, in large part, precipitated as copper carbonate (Hutchinson, 1957). That the variability in hardness among the eight study lakes is not great could have accounted for the lack of a trend in the occurrence of this element. Furthermore, although some hardness was present, these waters might also have been too soft for precipitation of ionic copper.

With one exception, total phosphorus levels were low. The value recorded for lake 45, 30 ppb, is in the range normally reported for surface waters. No correlation between total phosphorus concentration and primary productivity was observed for these lakes.

Zinc, molybdenum, cobalt, and vanadium were found in trace amounts. Primary-productivity experiments conducted with trace-element (Fe, Mo, B, Zn, Mn, Co, Cu) fortification of pond water indicated that trace-element enrichment inhibited phytoplankton carbon fixation rates (Gordon, 1969). Evidence suggests that these essential elements found only in trace amounts are not limiting lake metabolism on Amchitka Island. (This topic is later developed more fully in the discussion of primary productivity.)

Little or no information pertaining to their concentration or their role in aquatic systems is available for many of the elements listed in Table 7. Nevertheless, these data are important because they will serve to augment the growing data base needed to elucidate element concentrations of the earth's surface waters.

Net Phytoplankton

For those lakes sampled, *Melosira*, *Ochromonas*, and *Dinobryon* dominated in early spring; *Asterionella formosa* dominated in a few of the more productive lakes. In lakes 9, 26, and 28, *Dinobryon* populations increased exponentially during dominance periods, indicating optimal conditions for the development of this genus.

The number of phytoplankton species in most of the lakes increases significantly during the summer. The Chlorophyta increase in importance. Members of the Cyanophyta become dominant in many of the more productive lakes. During the summer pulse the lakes may be divided into three general types: (1) those which maintain a predominance of Chrysophyta; (2) those which support populations of numerous diatoms and Chlorophytan species, including populations of desmids and filamentous Zygnematales; and (3) those which contain large populations of filamentous and colonial Cyanophyta. The first type is common to acid bog lakes throughout northern regions, the second is representative of less productive acid and neutral northern lakes, and the third is atypical of northern regions unless a source of nutrient enrichment is present.

Numerous small pools and lakes on Amchitka are of the Chrysophyte type, for example, lakes 7, 9, and 10, but the vast majority of lakes and ponds are of the second type, supporting mixed populations of diatoms and desmids. Lakes 15, 18, 51,

and 57 contained large populations of filamentous Zygnematales.

On Amchitka the third lake type is of special interest. Lakes 1, 1a, 2, and 5 clearly belong in this category. Lakes 2 and 5 lie in an area that was thickly inhabited by military troops during World War II. The natural terrestrial habitat experienced extensive destructive disturbance. Excavation undoubtedly increased the silt load passing into these lakes. The frequent use of numerous outhouses produced a significant subsurface store of nutrients. The slow mineralization and dissolution of human excreta may have provided a small but continuing source of nutrients over the years. However, since no phytoplankton survey was conducted on the island before this investigation, the impact of such nutrient sources on the biotic composition of the lakes can only be surmised.

Lakes 1 and 5 receive nutrient-enriched (especially by phosphate) water from underground springs, and the effect is clearly evident. Both lakes become highly turbid during the summer with dense blooms of *Anabaena flos-aquae* and/or *Aphanizomenon flos-aquae*. Lake 1a receives nutrient input from the outflow of water from the sewage lagoons serving the AEC camp. This lake has dense blue-green algal blooms consisting primarily of *Aphanizomenon flos-aquae*.

The net phytoplankton genera found on Amchitka Island are:

Division Chlorophyta

Class Chlorophyceae

Order Zygnematales

Family Zygnemataceae

Mougeotia C. A. Agardh

Spirogyra Link

Zygnema Agardh

Zygogonium Kuetzing

Family Mesotaeniaceae

Gonatozygon de Bary

Family Desmidiaceae (Desmids)

Arthrodesmus Ehrenberg

Closterium Nitzsch

Cosmarium Corda

Cosmocladium Brebisson

Euastrum Ehrenberg

Hyalotheca Ehrenberg

Micrasterias Agardh

Pleurotaenium Naegeli

Penium Brebisson

Sphaeroszoma Corda

Spondylosium Brebisson

Staurostrum Meyen

Order Tetrasporales

Family Palmellaceae

Sphaerocystis Chodat

Gleocystis Naegeli

Family Tetrasporaceae
Tetraspora Link
Order Ulotrichales
Family Ulotrichaceae
Geminella Turpin
Hormidium Klebs
Ulothrix Kuetzing
Family Coleochaetaceae
Coleochaeta de Brebisson
Order Cladophorales
Family Cladophoraceae
Cladophora Kuetzing
Order Oedogoniales
Family Oedogoniaceae
Bulbochaete C. A. Agardh
Oedogonium Link
Order Chlorococcales
Family Botryococcaceae
Botryococcus Kuetzing
Family Chlorococcaceae
Golenkinia Chodat
Family Hydrodictyaceae
Pediastrum Meyen
Family Oocystaceae
Ankistrodesmus Corda
Dictyosphaerium Naegeli
Franceia Lemmerman
Oocystis Naegeli
Westella de Wildemann
Family Scenedesmaceae
Scenedesmus Meyen
Division Chrysophyta
Class Xanthophyceae
Tribonema Derbes & Solier
Class Chrysophyceae
Dinobryon Ehrenberg
Hyalobryon Lauterborn
Ochromonas Wyssotzki
Uroglena Calk
Class Bacillariophyceae (Diatoms)
Amphora Ehrenberg
Asterionella Hassall
Eunotia Ehrenberg
Fragillaria Lyngbye
Gomphonema Agardh
Gyrosigma Hassall
Melosira Agardh
Pleurosigma W. Smith
Rhizosolenia Ehrenberg emend Brighton
Surirella Turpin
Synedra Ehrenberg
Tabellaria Ehrenberg
Division Cyanophyta
Family Chroococcaceae
Agmenellum Brebisson
Anacystis Meneghini

Coccochloris Sprengel
Family Stigonemataceae
Hapalosiphon Naegeli
Family Nostocaceae
Anabaena Bory
Aphanizomenon Morren
Nodularia Mertens
Nostoc Vaucher
Family Rivulariaceae
Tolypothrix Kuetzing
Family Oscillatoriaceae
Lyngbya Agardh
Oscillatoria Vaucher

Zooplankton

Since zooplankton populations can wax and wane within a several-day period, averaging and tabulating quantitative estimates of zooplankton densities obtained from the study lakes over the years is futile. Available data do indicate several trends, however.

Rotifers dominate the zooplankton populations in Amchitka's lakes and ponds. Although a few lakes and ponds support cladocerans and copepods, the number of these organisms is insignificant compared with that of rotifers. Rotifers were distributed widely over the island, copepods were sporadic, and cladocerans were commonly absent.

Six genera of rotifers were identified: *Keratella*, *Polyarthra*, *Asplanchna*, *Synchaeta*, *Filinia*, and *Conochilus*. Although *Polyarthra* occurred most often in terms of distribution, *Keratella* usually dominated the rotifer biomass in those lakes where it occurred. Two species of the genus *Keratella* were present: *K. quadrata* and *K. cochlearis*. Of the two, *K. quadrata* reached much higher population densities than did *K. cochlearis*. Maximum rotifer densities (organisms/liter) observed during the study period were as follows: *K. quadrata*, ~6400; *K. cochlearis*, ~1100; *Polyarthra*, ~1200; *Asplanchna*, ~900; *Synchaeta*, ~50; and *Filinia*, ~500. Lakes 1, 1a, 2, 5, 9, and 10 and Cannikin Lake supported rotifer populations of relatively high density.

Most areas sampled contained small to moderate populations of copepods. At least three or more species of copepods are present on Amchitka, but resources have not permitted enumeration of these organisms by specie designation. A species of red copepod has been collected from some of the lakes and has been particularly abundant in samples from lakes 42f and 43b. Although red-colored sediment occurs in these lakes, the red color imparted to the copepod is not due apparently to ingestion of sediment particles. These organisms have been maintained in spring water for several

days without any noticeable color loss. The coloration is apparently concentrated in the oils in the copepod, and its source is, so far, unknown. Until the formation of Cannikin Lake, all the copepods found on the island were of the calanoid type; copepods that have established in Cannikin Lake are of the cyclopoid type. Copepod distribution and abundance were very sporadic. The highest density recorded was 220 organisms/liter in lake 9; on some occasions copepods were not found in this lake.

Only two cladoceran genera were found, *Bosmina* and *Allona*. All regions sampled contained at least one lake with small cladoceran populations. Lakes 5, 28, 42e, 42f, and 42d occasionally had a maximum standing crop as high as 200 organisms/liter. However, cladoceran density in many other lakes was commonly less than 10 per liter. Cladocerans and copepods may be considered relatively unimportant components of the zooplankton communities on Amchitka Island.

An intensive study of zooplankton distribution and the abiotic and biotic factors influencing distribution should produce interesting ecologic data. Cladocerans tended to be in acidic brown-water lakes, but the pattern was never very distinct. Rotifers seemed to proliferate in the more productive alkaline lakes. Hobbie (1973) suggests that primary productivity in Arctic waters affects plankton community composition in such a manner that, as a lake progresses from extremely oligotrophic toward the other end of the spectrum (eutrophic), more food (energy) becomes available, allowing greater niche diversity. The scheme suggests that the order of increasing diversity is as follows: phytoplankton, rotifers, calanoid copepods, cyclopoid copepods, and cladocera. With few exceptions this scheme coincides with plankton abundance found on Amchitka. Exceptions were the presence of cladocera but the absence of cyclopoid copepods (excluding Cannikin Lake) and the absence of calanoid copepods in Cannikin Lake. The development of the zooplankton community in Cannikin Lake was associated with dramatic increases in primary productivity. When this lake was first sampled during spring 1973, primary productivity was very low (Table 8) and zooplankters were rare. Work conducted during late summer 1973 revealed that primary productivity had increased about 30-fold, rotifers were very abundant, cyclopoid copepods were numerous, and a few cladocera were present (Burkett, 1974).

Primary Productivity

Primary-productivity measurements were conducted for 27 lakes. Experiments during the

autumns of 1967 and 1968 were conducted in situ during midday. Similar field experimentation was repeated again during autumn 1972, but on this occasion incubations were conducted throughout the day. Unless indicated in Table 8, all other values for carbon fixation rates were obtained by laboratory experimentation as previously described. Although in situ determination of primary productivity is advantageous because it provides the most accurate estimate of actual productivity for a lake at a particular time, such measurements on Amchitka may be quite variable owing to extreme variations in incident radiation and/or turbidity at the time of incubation. Solar insolation at Amchitka is commonly low owing to cloud cover but can be extremely erratic on days when the sky is not completely overcast.

Although these productivity data do not distinctly indicate whether productivity was highest in spring or in autumn, field observations indicated a greater frequency of algal blooms during springtime. The highest carbon fixation rate observed, $119 \text{ mg C m}^{-3} \text{ hr}^{-1}$, was for water obtained from lake 1a, which received nutrient input via outflow from the sewage containment ponds serving the AEC camp. Although productivity estimates are not available for lake 1a before the arrival of personnel for the nuclear test program, comparison with productivity data for other lakes indicates that inflow of nutrient-enriched water to this lake produced a dramatic rise in the carbon fixation rate. The response of lake 1a to elevated nutrient influx is similar to that reported by Nelson and Edmondson (1956) on fertilizing Bare Lake, Alaska. This suggests that primary-productivity rates many times higher than those observed in most Amchitka lakes might be obtainable in the Amchitka environment were it not for a deficiency of nutrients.

Productivity data for individual lakes exhibit considerable variability over the study period owing, probably, to the different times at which algal biomass in the study lakes was sampled. Values determined using in situ incubations were not always higher than estimates derived using laboratory incubations. Note data for lakes 9, 29, 30, and 36, for example. Whether or not light inhibited or enhanced photosynthetic activity by phytoplankters during laboratory incubations is unknown. Experimentation during autumn 1972 on lakes 5, 29, 30, and 31b indicated that in situ incubations at midday yielded the highest productivity rates.

Primary-productivity measurements for Cannikin Lake were first made during the spring of 1973. Because of the size of the lake, experimen-

Table 8—Carbon Fixation Rates for Amchitka Lakes

Lake	Carbon fixation rate, mg C m ⁻³ hr ⁻¹										
	Autumn 1967	Spring 1968	Autumn 1968	Spring 1969	Spring 1970	Spring 1971	Autumn 1971	Spring 1972	Autumn 1972	Spring 1973	Autumn 1973
1		9.7	9.1*	3.2	4.1 6.4			8.2	4.5		
1a								119.7			
2				0.5				11.9	9.2		
5				9.2	14.9 10.3			14.1	7.7* (0834-1235)† 16.3* (1230-1630)† 2.5* (1630-2030)†	2.9	
9		5.2	12.1*	2.8	12.1	31.5	5.4	3.9	1.0		
10					5.3	11.5	20.9	1.8	7.5	2.5	
19b								0.3	1.3		
26	8.1*	3.6	7.2*	0.5	2.5	3.8	0.4	0.6	1.6		
28		4.8	16.1*	5.4	10.9			1.6	2.7		
29		0.8	0.3*	0.4	0.9		0.3	0.2	0.4* (0815-1230)† 0.4* (1230-1620)† 0.3* (1600-2000)†		
30				3.9	11.6		0.3	0.7	0.7* (0815-1215)† 2.1* (1220-1620)† 0.5* (1600-2000)†		
31b		1.7	20.6*	0.6	1.6	5.4	2.3 0.3	1.0	0.6* (0800-1200)† 1.5* (1200-1600)† 0.7* (1555-1955)†	0.3	
33		1.6	1.5*	0.1	0.4						
35	2.5*				7.6						
36	0.8*			2.0	4.2						
42c						2.5	1.8				
42d						0.6	0.7				
42e							1.5				
42f						2.3	0.7	2.1	4.7		
42g								0.9	0.5		
43b						0.6	0.8	1.2	2.2		
43c							0.4 2.5 0.8				
43d								1.0	0.6		
58a		0.6	1.6*	0.4	0.2		0.3	0.2	0.3		
Cannikin											
Sta. 1 (0.2m)										0.3	9.5
(2.0m)										0.3	
Sta. 2 (0.2m)										0.3	8.9
(2.0m)										0.3	
Sta. 3 (0.2m)										0.2	9.2
(2.0m)										0.3	
Sta. 4 (0.2m)										0.3	7.9
(2.0m)										0.3	

*In situ incubation.

†Incubation period, Bering Daylight Time.

tion was conducted with water samples collected from two depths at four stations to help overcome any intrinsic sampling bias due to uneven distribution of phytoplankton. Results indicated that carbon fixation rates were lower in Cannikin Lake than in other lakes during this period. No significant differences due to depth were found among these data for Cannikin Lake. Furthermore, the variation that occurred between stations was slight. Work conducted to assess productivity in this lake

was repeated during the autumn of 1973. Comparison of spring and autumn data indicates a marked rise in the rate of primary productivity in Cannikin Lake. Secchi disk visibility was 160 cm during spring and 145 cm during autumn. These measurements were made at the time water samples were obtained for the primary-productivity experiments. Apparently, establishment and growth of the biologic community were accelerated during the intervening summer period.

Although numerous authors attempt to make comparisons between primary-production data obtained from lakes of widely varying geographical regions, no serious attempt is made here to mimic such practice. Suffice it to say that for Amchitka, with its maritime climate, the primary-productivity rate for some lakes is similar to that reported for Arctic tundra lakes (Hobbie, 1973). The production rate in lake 1a (the recipient of excessive nutrient inputs) reached a level similar to that reported for western Lake Erie during summer (Cody, 1972). It might be surmised that, when the supply of mineral nutrients is not a limiting factor, the maximum rate of algal photosynthesis attained is very likely to be similar even among lakes in different climate zones.

Research was conducted to elucidate the environmental factor(s) limiting algal photosynthesis in the lakes and ponds on Amchitka Island (Gordon, 1969; Koob, 1968; Youger, 1970). In summary, the separate and combined addition of phosphate and nitrate had diverse effects on algal photosynthesis in lakes 1, 9, 15, 26, 28, 29, 31b, 33, 35, 36, and 58a. Following the addition of these nutrients to lake-water samples, response varied from photosynthetic enhancement to inhibition. Trace-element fortification of water from lakes 15, 26, 35, and 36 inhibited carbon fixation by phytoplankton. Overall, phosphate was judged the principal limiting nutrient in many of the 11 study lakes mentioned above.

As a further check on this conclusion, an alkaline phosphatase enzyme assay (Fitzgerald and Nelson, 1966) was used to determine whether the algae were indeed living under inorganic-phosphate starvation conditions. With this test a positive reaction indicates the presence of the enzyme alkaline phosphatase, which in turn is produced in the absence of free reactive inorganic orthophosphate in the water in which the algae are growing. Positive results were obtained for lakes 9, 15, 26, 31b, 33, 36, and 58a (Koob, 1969).

Organic Matter

Organic-matter concentration was measured in open lake water and in the inlet and outlet streams of the lakes sampled (Birch, 1972; 1973; Koob, 1971a). A portion of the resultant data is shown in Table 9. These data do not represent organic-matter budgets since detailed hydrologic data on stream flow and lake volume are not available. These investigations were initiated to determine the relative importance of allochthonous and autochthonous materials to lake metabolism on Amchitka. Organic matter present in the lakes is derived naturally from several sources. Allochtho-

Table 9—Open Lake-Water Productivity and Organic Matter in the Inlet Streams, Open Lake Water, and Outlet Streams

Lake	Date	Location	Total organic matter, mg/liter	Primary productivity, mg C m ⁻³ hr ⁻¹
1	Autumn 1968	Inlet	5.4	9.1
		O.L.W.	15.7	
		Outlet	16.7	
	Spring 1969	Inlet	2.8	3.2
		O.L.W.	3.5	
		Outlet	3.8	
2	Spring 1972	Inlet	2.4	11.9
		O.L.W.	5.7	
		Outlet	8.8	
5	Spring 1969	Inlet	5.6	9.2
		O.L.W.	6.2	
		Outlet	5.6	
	Spring 1972	Inlet	5.3	14.1
		O.L.W.	7.2	
		Outlet	10.7	
9	Spring 1969	Inlet	6.0	2.8
		O.L.W.	4.7	
		Outlet	4.0	
19b	Spring 1972	Inlet	5.5	0.3
		O.L.W.	7.8	
		Outlet	6.3	
26	Autumn 1968	Inlet	8.1	7.2
		O.L.W.	12.2	
		Outlet	13.5	
	Spring 1972	Inlet	7.4	0.6
		O.L.W.	6.7	
		Outlet	7.8	
28	Autumn 1968	Inlet	7.3	16.1
		O.L.W.	7.3	
		Outlet	7.3	
	Spring 1969	Inlet	4.6	5.4
		O.L.W.	5.8	
		Outlet	8.2	
29	Autumn 1968	Inlet	11.7	0.3
		O.L.W.	6.4	
		Outlet		
31b	Autumn 1968	Inlet	4.9	20.6
		O.L.W.	6.9	
		Outlet	6.2	
	Spring 1969	Inlet	6.2	0.6
		O.L.W.	4.8	
		Outlet	5.5	
36	Spring 1969	Inlet	2.3	2.0
		O.L.W.	1.5	
		Outlet		
42g	Spring 1972	Inlet	7.4	0.9
		O.L.W.	6.7	
		Outlet	6.5	
58a	Autumn 1968	Inlet	3.4	1.6
		O.L.W.	0.3	
		Outlet	0.3	

nous organic inputs enter from inlet streams, from bank erosion due to wave action, and from waterfowl excreta. Windblown matter is probably an additional extrinsic source. Autochthonous organic matter arises from intrinsic biologic production, from decomposition processes, from resuspension of precipitated organic materials in surficial sediment, and from release of excretory organics by indigenous aquatic biota. Organic matter in aquatic ecosystems functions in at least three ways: (1) it is a food source for detritus

feeders, (2) it may serve as a substrate for growth of bacteria and other microorganisms, and (3) in the form of dissolved organic compounds it represents exogenous growth substances, vitamins, and chelating agents (Lind, 1971).

For most of the lakes, organic-matter concentration in the open lake water and/or outlet stream was greater than concentrations found for the inflow streams. This suggests an autochthonous rather than an allochthonous pattern of organic supply. That differences occurred between concentrations of organic matter in lake water vs. outflow for some systems is unexplained since outflow water was expected to be characteristically similar to open lake water. Perhaps these differences are due to sampling error. Intrinsic production of the major portion of organic matter is the common condition in most lakes, but a few very unproductive lakes receive significant amounts of organics from their drainage basins. Lakes 29 and 58a possibly reflect this condition.

Heterotrophy

Little is known about the dynamics of bacteria in aquatic systems. Heterotrophic activity by bacteria is recognized, however, to be of great importance in recycling materials through the detrital food web of aquatic systems. Estimates of heterotrophic bacterial activity were made with $2\text{-}^{14}\text{C}$ -labeled sodium acetate as a metabolic substrate. Theoretical maximum uptake rate for acetate (V_t) served as a relative estimate of the sizes of the active bacterial populations able to use acetate as a metabolic substrate. Some V_t values are listed along with organic-matter concentrations and dark-bottle carbon fixation rates in Table 10. These data indicate a direct relation between V_t and organic matter. With the exception of lake 9, nonphotosynthetic carbon fixation was lowest in lakes having both low V_t values and organic-matter concentration. Additional data, discussed by Koob (1971b), indicated a statistically significant relation of V_t as a function of the log of the concentration of total organic matter.

Perturbations

Two small lakes near Milrow SZ were partially drained when a shallow collapse crater formed around SZ after detonation. Changes observed in other lakes following Milrow were slight; most were attributed to seasonal fluctuation and were not considered to be the result of Milrow. Natural shifts in physical and chemical parameters plus changes in rates of metabolic parameters (heterotrophy and primary productivity) were not altered observably by Milrow. No elimination of

Table 10—Comparison of Bacterial Activity, Nonphotosynthetic Carbon Fixation, and Organic-Matter Concentration in Amchitka Lakes, Spring 1969

Lake	V_t , $\mu\text{g acetate}$ $\text{liter}^{-1} \text{hr}^{-1}$	Organic matter, mg/liter		Dark carbon fixation, $\text{mg C m}^{-3} \text{hr}^{-1}$
		Total	Dissolved	
1	0.18	3.5	3.2	2.2
5	0.11	6.2	3.8	5.2
9	0.14	4.7	3.0	0.5
28	0.16	5.8	4.9	2.2
36	0.02	1.5	1.1	0.3
58a	0.03	2.8	1.0	0.2

planktonic species or drastic change in plankton community structure was observed.

Detonation of Cannikin resulted in (1) gross morphological changes to several lakes near SZ (complete or partial drainage, tilting, and bottom fissuring); (2) rupture of a dike in a drill-mud containment pond with subsequent contamination of an adjacent creek; and (3) formation of a new lake, Cannikin Lake, in the Cannikin subsidence crater.

Observations of potential short-term effects on chemical and biological parameters in Amchitka lakes as a result of Cannikin were masked by the separate effects of a severe storm immediately preceding detonation and by the effects wrought from unusually low amounts of rainfall the following spring. Longer term post-Cannikin reconnaissance has not produced evidence to indicate that any significant changes in chemical and biological parameters occurred due to the Cannikin ground shock wave.

Several aquatic habitats were seriously altered as a result of drilling operations and general support activities. The influx of drilling mud and associated materials into three lakes seriously altered their chemical, physical, and biological characteristics. In one instance, drill mud was pumped into 14-Mile Lake for storage. This lake is no longer a freshwater habitat capable of supporting aquatic life. Additionally, contaminated water from 14-Mile Lake entered lake 51, causing deterioration in water quality and loss of aquatic life. However, since the drilling materials were somewhat diluted prior to entering lake 51, this system might recover within a few years. A small pond at D-site received outfalls of drill-mud wastes from adjacent holding ponds and was rendered useless as an aquatic habitat. Moreover, the pond drained into Falls Creek, producing attendant adverse effects there too. These waterbodies might recover their predisturbance status following evacuation of the island. Streams perturbed by drill-mud influx appear to be recovering slowly.

Lake 1a receives considerable nutrients from the effluent of a sewage settling pond serving the main camp area. The principal effect has been a dramatic increase in rate of primary productivity. Recovery rate for this pond is linked to the rapidity by which nutrients will be flushed from the lake following evacuation of the island.

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Aquatic Ecology

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The freshwater ponds and streams of Amchitka support few species of vertebrates and invertebrates. Aquatic community structure is therefore simple, and only three major trophic levels can be recognized: primary producers (benthic periphyton and vascular plants), primary consumers (invertebrates), and secondary consumers (fishes).

Production by periphyton and vascular plants in streams is low. Most of the streams are evidently heterotrophic since the shower of detritus from streamside and pond vegetation exceeds that produced in the channel. Immature insects, particularly midges, use this organic matter and serve as the principal food of Dolly Varden, threespine stickleback, coast-range sculpin, and immature silver salmon. Pink salmon and occasionally sockeye salmon also use the island streams for spawning.

The two underground nuclear detonations, Milrow and Cannikin, had profound effects on those ponds and streams within about 2 km of surface zero (SZ). Ponds were drained by fissuring or tilting, and stream channels were altered. Local fish populations suffered from these terrain alterations and from pressure waves generated by the blasts.

Extensive effects on freshwater communities were observed before these events, when the emplacement shafts were being drilled. Mud spills from the drilling operations released hazardous chemicals and heavy particulates into nearby streams, which decimated fish and invertebrate populations. The invertebrates were killed by the concentration of petroleum products and by the suffocating effects of compacted muds. The fish populations failed because of the chemicals and muds as well as the reduction of their principal food source, the midges. Once the mud spills abated, flushing action in the short streams enhanced the expulsion of the drilling muds. The perturbed communities exhibited a high degree of resilience. Recolonization of these allochthonous streams ensued rapidly as long as brood stocks were available. The effects of the two nuclear events on the freshwater communities were limited to waters within 2 km of SZ of each device. In those ponds or streams where habitat alteration was not permanent, the fish populations recovered fully within 5 years of each event.

Studies of freshwater ecosystems on Amchitka were undertaken primarily to (1) develop an ecological base line of the unperturbed aquatic ecosystems on the island, (2) observe and measure the effects on the aquatic ecosystems of perturbations resulting from underground nuclear testing and preparation for testing, and (3) develop a basis for ecological predictability in the aquatic ecosystems concerning effects of perturbations.

The approach to this study was empirical, starting with an initial survey and followed by in-depth characterization of selected stream and pond ecosystems. The initial survey work was begun in August 1967. This survey was intended to establish the extent of different freshwater ecosystem types. More intensive studies were conducted on selected areas of both streams and ponds representative of the types identified in the initial survey. Eventually, a compartmental model of the type of stream most likely to be affected by testing was constructed to aid in the evaluation of these effects. Major study areas are shown in Fig. 1.

DESCRIPTION OF FRESHWATERS

Physical

Amchitka can be divided into three physiographic regions: southeastern, central, and northwestern. The southeastern region is a lowland with mild relief and streams relatively low in volume, gradient, and velocity. The basins drained by these streams contain many small, shallow ponds with relatively uniform and consistent bottoms.

The central region is higher in elevation. The ponds here resemble those of the southeastern region but are confined to a large plateau along the main ridge of the island. The streams draining these basins increase in gradient as they approach the sea; some enter the sea as cascading waterfalls whereas others flow between steep sea cliffs.

Ponds in the mountainous northwestern region of Amchitka are fewer in number and located either at the heads of drainage basins or in shallow basins on plateaus near the coast. The streams in this area cascade to the sea as alternating pools and

Fig. 1—Location of study sites on Amchitka Island.

riffles, and they usually have a higher volume of flow and gradient than do the streams in the southeastern and central regions.

All watersheds on Amchitka are limited to 2 to 5 km in length since all streams drain perpendicular to the long axis of the island into either the Bering Sea or the Pacific Ocean (Fig. 1).

Streams (Fig. 2)

Lowland Streams. The streams of southeastern Amchitka meander through tundra-covered watersheds (Fig. 2a). Overhanging banks provide substantial cover for fish. In some upstream areas the banks meet and form a solid turf roof over the stream. Near the outlet most streams flow 1 to 3 m wide and 20 to 30 cm deep.

The average gradient for four of the larger southeastern streams is 14 m/km for the last 2 km nearest the outlet (a range of 7 to 20 m/km). There are few riffles in these streams; most are characterized by long slow-flowing pools. The average velocity of the four streams in the summer was 0.3 m/sec.

The substrate of these lowland streams is predominantly soft organic muck, which supports an abundance of perennial plants. There are very few gravel or rocky areas except near the outlets. The aquatic vegetation is very desirable cover for fishes, but the sparsity of gravel for spawning by anadromous salmonids appears to limit their numbers in some streams.

The flow of lowland streams on Amchitka varies markedly, even on a daily basis. The volume of water in a stream is strongly dependent on both the amount of immediate rainfall and the moisture in the relatively thin soil layer and tundra mat of the watershed. Amchitka receives relatively little precipitation from March to June (Fig. 3). This allows the moisture content of the soil and organic mat to decrease appreciably (Fenske, 1972). Stream volume during this time decreases accordingly. An increase in the frequency and intensity of precipitation in July results in little or no increase in stream volume because of the dry soil and tundra. Once the terrain is saturated, by about September, any small amount of precipitation is manifested in considerable increases in stream flow. This "sponge effect" is a very significant phenomenon in relation to timing of migration by anadromous salmonids in these small Amchitka streams. In addition, the freshets created by heavy rainfall provide a strong flushing action in the watershed and stream, which aids in the release and distribution of organic detritus through the stream system.

Fig. 2—Representative freshwater streams of Amchitka. (a) Bridge Creek, a lowland stream meandering through tundra. (b) Chitka Cove Stream, a midland stream temporarily blocked by a gravel dike. (c) Northwest Camp Stream, a highland stream flowing over a 10-m-high sea cliff. (Photographs courtesy of Carl Abegglen, U. S. Fish and Wildlife Service.)

Midland Streams. The midland streams of the central region of Amchitka generally meander less than the lowland streams. The width of most of these streams is 2 to 4 m, and the depth varies from 20 to 30 cm. The average gradient of four of these midland streams is 25 m/km for the last 2 km nearest the outlet (a range of 15 to 32 m/km). The most notable feature of these streams is the presence of a bedrock substrate over much of the

Fig. 3—Average flow rates of Bridge Creek and corresponding precipitation measured at the Amchitka air terminal during 1968. (Data courtesy of the U. S. Geological Survey.)

length of the stream. Depositions of gravel are found near the outlets, and accumulations of silt and clay occur in the backwashes. Spawning of anadromous salmonids is restricted to this gravel near the outlet and that by landlocked forms to isolated deposits of gravel in rivulets high upstream.

Highland Streams. The streams of mountainous northwestern Amchitka meander less and have a greater volume and velocity of flow than the lowland streams. These mountain streams are geologically young, cutting streams that flow from springs or ponds on the plateau of the ridge bisecting the island. Most flow through deep tundra-covered valleys. These streams are more open than those in southeastern Amchitka; turf roofs, or areas where opposing stream banks have grown together, are only over sections high upstream. Most highland streams have an outlet 2 to 4 m wide and 25 to 35 cm deep.

The average gradient for four of the larger highland streams is 70 m/km for the 2 km nearest the outlet (a range of 32 to 95 m/km). The streams in this region of Amchitka cascade to the sea with alternating pools and riffles over substrates of rubble, gravel, coarse sand, and exposed bedrock.

Flow in the highland streams is as dependent on precipitation and soil moisture as it is in the lowland streams. Precipitation in the highlands is probably greater than that measured at the air terminal in the southeastern region of the island.

Ponds

Freshwater ponds are a conspicuous feature of the Amchitka landscape. Such ponds are found throughout the island, but they are most numerous in the southeastern region, where they occur with

an average frequency of over 10 ponds per square kilometer. McCann* reported that there were more than 2100 ponds in the southeastern region, although he noted that some were intermittent. Of 60 ponds selected by McCann for observation, about half were less than 0.4 ha (1 acre) in surface area, and three-fourths had an area of less than 0.8 ha (2 acres); the largest pond had a surface area of 27 ha (67 acres).

Origin. Most of the pond basins in southeastern Amchitka appear to be phytogenic in nature. Some lack a definite inlet or outlet or both. These basins were probably formed by locally uneven accumulations of snow, which resulted in uneven growth of tundra vegetation. These retarded patches formed peat less rapidly than the surrounding area; so enclosed depressions were formed. Many of these pond basins were undoubtedly also formed by local thawing of buried ice wedges or of frozen soils. These ponds resemble those described by Hutchinson (1957) when referring to arctic and subarctic situations.

A number of pond basins in northwestern Amchitka also appear to be phytogenic, but most are rocky with irregular shorelines and rapid changes in depth. Although the island is principally andesite rock, the origin of these tectonic ponds is probably not volcanic; they probably were formed by the deformation of the earth's crust.

Bottom Composition. Most phytogenic basins on Amchitka are characteristically flat with irregularly shaped shorelines and deeply undercut banks created by wave action from persistent winds. A band of partially buried boulders and large irregularly shaped rocks makes up the periphery of many of these basins. There are few sandy beaches in any of these ponds. A rapid transition of rock to silt, with soft organic muck, occurs toward the center of most of these basins. Submergent and emergent vegetation grows abundantly from this substrate in the summer months. Shoreline vegetation is sparse, probably because of the rocky substrate and constant wave action.

The tectonic basins of the highlands are mostly rocky and deeper than the phytogenic ponds. Boulders and large irregularly shaped rocks lie buried or partially buried in soft muck. Aquatic vegetation grows from the center and shore of these basins, although the flora is not as rich as that of the phytogenic ponds. Basin floors are largely uneven with rapid changes in depth. Each of these ponds possesses an outlet stream and most, an inlet stream as well.

*John A. McCann, 1963, unpublished report in files of the U. S. Fish and Wildlife Service, Anchorage, Alaska.

Interfaces

Pond to Stream. Many small phytogenic ponds on Amchitka lack definite outlet or inlet streams or both. These ponds receive runoff from rainfall or from seepage through the tundra mat. Some of the basins are completely dry in spring and early summer when precipitation is lowest. Most large basins on plateaus or on small rises receive runoff in the form of small rivulets, which flow under completely overgrown banks. The outlet streams are often more distinguishable but retain the same characteristic overgrown banks for much of their length or until a major stream is reached. Aquatic vegetation is so abundant in these streams in the summer months that where the channel is not covered by a turf roof it is well marked by the lush, heavy growth of plants. The water surface of these streams is often far below the level of the tundra surface.

Stream to Ocean. An aerial survey of Amchitka streams revealed that, of 73 perennial streams draining both the highlands and lowlands of the island, only 30 flowed unimpeded into the sea. The remainder either spilled over sea cliffs or were blocked at their outlets by gravel or sand dikes.

Seventeen of the unimpeded streams were in the southeastern and central regions of the island. The outlets of these streams are lined with gravel, smooth rocks, rubble, and, sometimes, irregularly shaped chunks of white marine coralline algae that are 10 to 30 cm in diameter. These white stone-like chunks are washed ashore during storms. The gentle gradient of the outlet of these open streams is important for access by the anadromous salmonids.

The outlets of seven streams in northwestern Amchitka were found to be periodically blocked by large gravel or sand dikes built up by wave action, especially during severe storms (Fig. 2b). The mouths of these streams are usually located at the far end of a bay or cove into which the force of wave action is apparently channeled. The streams often percolate through these gravel dikes. Because of the changing conditions of these stream outlets, upstream and downstream movement by anadromous salmonids is not always possible.

Of the 73 streams visited on Amchitka, 36 flowed into the sea over cliffs ranging from 1 to 10 m in height (Fig. 2c). Most of these spilled onto rubble or boulders while cascading into the sea. The majority of these precipitous outlets were of streams in northwestern Amchitka. Although all these streams support small populations of landlocked Dolly Varden (*Salvelinus malma*), no anadromous salmonids inhabit them.

Biological—Distribution and Life Cycles

Three major energy assimilation, or trophic, levels were recognized in the freshwater ecosystems of Amchitka. The first was the photosynthetic level, composed of benthic periphyton and vascular plants in streams and benthic periphyton, vascular plants, and phytoplankton in ponds. The second recognized level was dominated by immature insects in streams and immature insects, crustaceans, and zooplankton in ponds. Six freshwater and anadromous fish species made up the third trophic level.

A greater diversity and abundance of aquatic vascular plants was found in the phytogenic ponds and lowland streams than in the tectonic ponds and highland streams of Amchitka. However, a remarkable similarity existed in the composition of macroinvertebrate species inhabiting the phytogenic and tectonic ponds; immature insects dominated the benthic fauna, and crustaceans dominated the rocky, littoral fauna.

This similarity was not reflected in the lowland and highland streams. Those immature insects and crustaceans best adapted to low-velocity flow and soft-mud bottoms dominated the fauna of the lowland streams. The highland streams supported forms able to attach to rocky substrates and tolerant of high-velocity flow.

Plants. Nineteen species of aquatic macrophytes, representing twelve families, were encountered in Amchitka ponds and streams (Table 1). These were mostly perennials, which overwinter mainly by means of persistent rootstocks. Some reproduce by seeds and spores. Shacklette et al. (1969) have thoroughly described these and other vegetative features of Amchitka.

The large mosses and leafy liverworts (*Fontinalis neomexicanus*, *Mnium* sp., and *Chiloscyphus* sp.) grow in nearly every stream on the island. *Fontinalis neomexicanus* provides an important habitat for many benthic and demersal invertebrates, which are an important food source for voracious young fishes. This large moss is abundant in lowland and highland streams but is most common in the higher gradient sections, where it grows attached to submerged stones in swift water.

The buttercup and water milfoil families are the only other vascular plant groups abundant in streams. *Caltha palustris* (marsh marigold) is often associated with *Hippuris vulgaris* (mare's tail) in mud substrates. The large brilliant yellow flowers of the marsh marigold emphasize its abundance in the lowland streams in June and early July. The *Fontinalis*–*Hippuris*–*Caltha* community provides excellent habitat for fishes in the lowland streams.

Table 1—Families and Species of Aquatic Macrophytes Encountered in Amchitka Freshwaters

Family Characeae (algae: stonewort, muskgrass)
<i>Nitella</i> sp.
Family Cyanophyceae (blue-green algae)
<i>Nostoc</i> sp.
Family Hepaticae (mosses and leafy liverworts)
<i>Fontinalis neomexicanus</i>
<i>Mnium</i> sp.
<i>Chiloscyphus</i> sp.
Family Equisetaceae (horsetail)
<i>Equisetum arvense</i> (scouring rush)
Family Isoetaceae (quillwort)
<i>Isoetes braunii</i>
Family Sparganiaceae (bur reed)
<i>Sparganium</i> sp.
Family Najadaceae (pondweed)
<i>Potamogeton vaginatus</i>
<i>P. crispus</i>
Family Cyperaceae (sedges)
<i>Carex macrochaeta</i>
<i>C. lyngbyaei</i>
Family Juncaceae (rushes)
<i>Juncus balticus</i>
Family Ranunculaceae (buttercup)
<i>Ranunculus reptans</i>
<i>R. trichophyllus</i>
<i>Caltha palustris</i> (marsh marigold)
Family Callitrichaceae (water starwort)
<i>Callitriche</i> sp.
Family Haloragidaceae (water milfoil)
<i>Myriophyllum spicatum</i>
<i>Hippuris vulgaris</i> (mare's tail)

The standing crop of this vegetative community remains high through the summer until October and November, at which time many of the stalks and leaves are shed. Much of this dead and dying vegetation is sheared and transported downstream by freshets caused by heavy rain or snow melt. *Fontinalis neomexicanus* and *H. vulgaris* contribute the greatest biomass to this detritus load. This phenomenon of detritus transport is not restricted to the winter season. The force of sudden rises in stream flow brought about by summer rains also shears some of this vegetation while it is still green.

The freshwater ponds of Amchitka, particularly the phytogenic ones, support a greater diversity and density of aquatic macrophytes than the streams. Perhaps the most evident plants are members of the water milfoil family, *H. vulgaris* and *Myriophyllum spicatum*. Both species flourish in the pond muds where their emergent nature makes their abundance evident. The underwater

forest created by these plants appears to be a highly desirable habitat for pond fishes.

The more abundant submergent forms of macrophytes in ponds include the pondweed *Potamogeton vaginatus*, a member of the bur reed family, *Sparganium* sp., and one species of buttercup, *Ranunculus trichophyllus*. The community formed by these three species is a thick mat of underwater vegetation that persists for the summer but dies down in the winter. The tiny delicate white flowers of *R. trichophyllus* are sometimes evident on the surface of phytogenic ponds in July and August.

Juncus balticus, *Callitriche* sp., *Isoetes braunii*, and *Myriophyllum spicatum* are limited in distribution to a very few ponds but are abundant where they occur. *Callitriche* sp. and *M. spicatum*, for example, form small windrows of vegetation on the windswept shores of Quonset Lake and Silver Salmon Lake (Fig. 1) when disturbed by severe winds. These often became a nuisance when entangled in gill nets and seines.

Perhaps the most novel of the aquatic plants on Amchitka is the large blue-green alga represented by the genus *Nostoc*. A few ponds on the island contain many of these free-floating gelatinous spheres of cells, which were commonly seen on wave-swept shores or in shallow water. Some, the size of tennis balls, were found in Silver Salmon Lake.

The muds of densely vegetated ponds often contained heavy loads of detritus. This detritus was eventually released into outlet streams, where it contributed significantly to allochthonous organic matter. Also contributing to this detritus in ponds and streams was the delicate terrestrial vegetation on eroding shorelines and sloughing banks.

In addition to the aquatic macrophytes, the photosynthetic component of Amchitka freshwaters is composed of an array of lower plants attached to submerged substrates. This diverse assemblage of algae, lichens, and diatoms makes up the producers in the benthic periphyton. Most grow attached to rocks, debris, or mud sediment. In the streams a combination of low year-around water temperatures and a dense canopy of aquatic macrophytes shading the benthos apparently hinders the photosynthetic process of the periphyton. The penetration of sunlight in ponds is similarly hindered by constant turbidity; so periphyton production in ponds is largely restricted to a narrow band of shallow water along the shoreline.

Macroinvertebrates. The second trophic level of the freshwater ecosystems, the primary consumers, is composed of a macroinvertebrate popu-

lation of low diversity. The more commonly occurring and biologically significant species are representatives of four phyla: Annelida, Nematoda, Mollusca, and Arthropoda. Palmisano (1971) and Valdez and Helm (1971) inventoried these and the less-common forms in lists of food items consumed by Dolly Varden and threespine sticklebacks, *Gasterosteus aculeatus*, on Amchitka.

Annelida and Nematoda. Annelids and nematodes are common only in ponds with soft-mud bottoms and at the outlets of streams in the area of tidal influence. Oligochaetes were frequently encountered in the gravel, sand, and bottom muds of stream outlets, and nematodes often abounded in decaying marine algae that had been tossed or washed into the stream by the tide. A few were found in the lake bottoms where detritus abounded or in newly flooded basins, such as the recently formed Cannikin Lake (Fig. 1). The two forms occurred occasionally in diets of fishes.

Mollusca. Pelecypods and gastropods occurred in all the large, muddy ponds sampled but were abundant in only about one-third of these. The former were represented by the fingernail clam, *Lymnaea abrusa*, and a larger species of clam, *Anodonta beringiana*. The small short snails, *Pisidium* sp., belonging to the family Lymnaeidae were commonly found with the small clams in pond muds.

The large mollusc *A. beringiana* was found in only one phytogenic pond on the island, aptly named Clam Lake (Fig. 1). The density of this clam was as high as three individuals per square meter of mud bottom. Empty shells and associated activity of wading birds along one shallow beach of this pond indicated some predation. This species of clam has an interesting association with coinhabiting fishes when in its larval or veliger stage of development (Barnes, 1968). Also known as the glochidium, the larva is small and bivalve in appearance. It possesses hooks by which to attach as a parasite on any of the various external structures of a fish. The glochidium encysts in fins or gills to gain nutrition from its host. Eventually the immature clam ruptures the cyst, settles to the bottom of the pond, and burrows into the mud where normal filter feeding ensues. Host fishes in Clam Lake were threespine sticklebacks and Dolly Varden.

Arthropoda. Two classes of arthropods, insects and crustaceans, dominate (in numbers) the macroinvertebrate fauna of Amchitka freshwaters. Few crustaceans were found in the streams except for amphipods of the genus *Hyallela*, which frequented the slow-flowing sections. An abundance

of crustaceans, including amphipods, isopods, and some mysids, was found in most large ponds.

The amphipod *Corophium spinicorne* was abundant along rocky pond shores and usually in association with attached filamentous algae. This amphipod is of great dietary importance to pond fishes (Palmisano, 1971; Valdez and Helm, 1971). Also abundant along these shores was the isopod *Gnorimosphaeroma lutea*, called the pillbug because of its propensity to curl up, head to tail, when alarmed or disturbed. It is also of great dietary importance to pond fishes. Although abundant in ponds, *G. lutea* was found in only one stream (Jones Creek), which empties into Constantine Harbor (Fig. 1).

Periodic collection of crustaceans in ponds and streams revealed that the amphipods (*Hyallela* sp. and *C. spinicorne*) as well as the isopods (*G. lutea*) of these subarctic waters had only one brood of young per year, these appearing in samples in late summer. The young of *C. spinicorne* and *G. lutea* were very abundant in green algae that grew on shoreline rocks of some ponds (Quonset Lake and Silver Salmon Lake).

A brackish-water mysid, *Acanthomysis awatchensis*, was found in stomachs of Dolly Varden and threespine sticklebacks from Silver Salmon Lake. Since this lake is connected to the Bering Sea via a short stream, it was suspected that the euryhaline fish had moved into the intertidal zone to feed on the mysids. The lack of fish movement through a weir did not support this hypothesis. Instead, the apparently euryhaline mysids probably moved into the pond where they were preyed on by the fishes.

Only a few species of aquatic insects inhabit the freshwaters of Amchitka. The most striking feature of this fauna is the complete absence of mosquitoes (Culicidae). Nevertheless, the orders Ephemeroptera (mayflies), Trichoptera (caddisflies), Diptera (blackflies and midges), Hemiptera (water boatmen), and Coleoptera (diving beetles) are common. In streams and ponds their larval or pupal stage or both are benthic or demersal by habit. A number of less-frequently occurring Diptera were reported in diets of Dolly Varden (Palmisano, 1971) and threespine sticklebacks (Valdez and Helm, 1971).

Only one genus of mayfly, *Pseudocloeon* sp., was found on Amchitka. The nymphal stage abounded only in the rock or rubble of streams with flow exceeding 0.75 m/sec. Most were encountered in northwestern highland streams where the substrate was free of mud and silt and the gradient was steep. The nymph of this genus is easily recognized by the presence of two long outer tail cerci and a very short central cerci. The form

may be easily mistaken for a plecopteran (stonefly), considering this feature and the hypognathus head structure. On Amchitka most adults emerged and oviposited once a year, in late September. Their life cycle is considered univoltine.

Both families of caddisflies on Amchitka were case builders. Members of the family Limnephilidae were abundant in muds of both ponds and streams. Cases were constructed of bits of twigs or leaves rather than of small pebbles as were those of the family Leptoceridae. Members of the family Leptoceridae, with their horn-shaped cases, were found predominantly in rocky streams and in the rubble of pond shores. They probably survived in the latter because of the constant overturn and circulation of water in these ponds caused by the perennial Amchitka winds. Most caddisflies on Amchitka are also univoltine.

Only two families of Diptera, Simuliidae and Chironomidae, were common. Larvae and pupae of simuliids were well distributed in slow-flowing rubble-bottomed streams, where they were attached to the underside of rocks or debris. The females of this stout round fly, also known as blackflies or buffalo gnats, are usually a menace to humans. This is not the case on Amchitka, because either their numbers are too low or the island is blessed with a species that is not bloodsucking.

The chironomids, or midges, certainly deserve the most attention of all the macroinvertebrates since their immature forms abound in mud substrates of both ponds and streams. Their high density and extensive distribution make them a very important primary consumer. The diet of freshwater fishes on Amchitka also demonstrates the importance of midges to the secondary consumers (Palmisano, 1971; Valdez and Helm, 1971). Dense clouds of adult midges were often seen swarming over the heavily vegetated streams in July and August but only on days with low to moderate wind. Although midges are formidable looking because of their resemblance to mosquitoes, they are nonbiting. Thus the human inhabitants of Amchitka are rarely bothered by biting insects of aquatic origin. The three species of midges identified on Amchitka are univoltine; the majority emerge and oviposit once a year, usually in late summer.

Fishes. Six species of fishes inhabit the freshwaters of Amchitka. Four are anadromous salmonids, including three Pacific salmon (silver, *Oncorhynchus kisutch*; pink, *O. gorbuscha*; and sockeye, *O. nerka*) and one char (Dolly Varden, *Salvelinus malma*). The fifth and sixth species are the threespine stickleback, *Gasterosteus aculeatus*, and the coast-range sculpin, *Cottus aleuticus*.

All six species are capable, at least for short periods, of a euryhaline existence, and the ways in which each arrived on this remote Aleutian Island are apparently related. The presence of these forms on Amchitka indicates postglacial dispersal from either the Bering or Pacific refuge sometime after the Wisconsin glaciation, about 10,000 years ago (McPhail and Lindsay, 1970). There is strong evidence that *G. aculeatus* and *C. aleuticus* survived in the Pacific refuge and dispersed northward along the coast. Apparently the freshwater form of the former arose subsequent to the arrival of the marine form. The three species of *Oncorhynchus* and one species of *Salvelinus* are believed to have survived in more than one refuge, but they probably dispersed to the Aleutians from the more proximate Bering refuge.

The life cycles of the four more common species on Amchitka (Dolly Varden, threespine stickleback, pink salmon, and silver salmon) are detailed in the following section as background for subsequent discussions. The distribution of the coast-range sculpin and the sockeye salmon on the island is also given.

Dolly Varden. The precipitous nature of the Amchitka shoreline, particularly in the northwest region, renders many of its streams and ponds inaccessible to anadromous salmonids. As a result, two morphologically and behaviorally distinct populations of Dolly Varden inhabit these waters; a dwarf landlocked form residing in the inaccessible ponds and streams and an anadromous form that, in adulthood, fattens at sea and spawns in the accessible island streams. The two forms were encountered sympatrically in accessible streams, but the density of the anadromous form far exceeded that of the landlocked form except above impassable waterfalls.

The landlocked form usually has a dark-olive-colored body with brilliant orange vermiculation and yellow margination of the ventral fins. The anadromous form, even as juveniles, exhibits a light greenish dorsal sheen and bright silvery sides. Both forms possess parr marks as juveniles, but only the landlocked form retains these in adulthood.

The origin of the two forms on Amchitka is conjectural, but apparently the anadromous form dispersed from the Bering refuge and gave rise to the landlocked form when changes in terrain and stream outlets isolated it from the marine environment. It is also likely that personnel stationed on the island during World War II transferred fish from one watershed to another, giving rise to at least some of the landlocked populations. All the approximately 70 perennial streams sampled and

about half the 60 or so ponds were inhabited by one of the two forms of Dolly Varden.

The life history of the anadromous Dolly Varden on Amchitka is much like that described for this char in southeastern Alaska (Armstrong, 1965; 1974) except that growth on Amchitka is slower and timing of migration differs. Upstream and downstream fish traps were established on Amchitka streams to monitor movement to and from the sea.

Dolly Varden hatch on Amchitka in February and March, usually under snow- and ice-laden streams. By June, after having absorbed their yolk sacs, the young leave their gravel redds and move into nearby stream vegetation, where they feed actively on immature insects and small crustaceans. At about 2 years of age, the young char begin to stray from the dense vegetation to the more open pools, using nearby undercut banks as shelter. Immature insects, principally midges, occurred in the freshwater diet of about 80% of these juvenile char and crustaceans (amphipods and isopods) occurred in about 40%. Only about 10% of the fish consumed molluscs, and a mere 5% ate fish or fish eggs (Palmisano, 1971).

Those immature fish closest to the sea often stray into the intertidal zone during high tide (apparently to feed) and then return to the stream before low tide. Anadromous char became smolts as age groups III and IV, or at about 100 and 130 mm standard length, respectively (Fig. 4). Parr marks began to fade, and major descent to the sea occurred in June and July, continuing intermittently throughout the summer (Fig. 5).

The abundance of food at sea enabled the sea-run Dolly Varden to maintain a rate of growth similar to that of the younger char in the streams (Fig. 6). The fish fed actively on intertidal invertebrates and small fishes. Young greenling (*Hexagrammos* sp.) and an assortment of amphipods and mysids made up over 50% of their diet at sea. Peaks in feeding usually occurred nocturnally near stream outlets and at high tide. Offshore gill-netting, purse seining, trawling, and long-lining for immature salmon by the University of Washington failed to capture any Dolly Varden farther offshore than about 1 km.* Apparently, char of Amchitka do not move offshore and may not even stray far from their natal stream since fish tagged in a stream were often recaptured feeding near its outlet.

Dolly Varden spent an average of about 73 days at sea, during which time average wet weight gained per fish was about 182 g (just over $\frac{1}{3}$ lb)

Fig. 4—Length-frequency histograms for seaward Dolly Varden and silver salmon smolts from a fish trap at Midden Cove Stream, July 1971. Age groups are designated by Roman numerals. N is the total number of fish.

and average increase in length was about 27 mm (Table 2).

Heavy rain in August and September swelled the small island streams and apparently facilitated an ascent by the anadromous char, which were often accompanied by adult pink salmon (Fig. 7). Large movements of these fishes occurred only during these freshets. Returning char had bright silvery sides with light green backs and were in excellent condition. The color of the fish began darkening after about 1 week in the stream, and, by spawning time in October and November, the males had turned a bright green atop with red sides and belly. This and the development of a kype on the mandible (an extension of the lower jaw) distinguished the male from the more drab greenish-colored female. Immediate degeneration of robustness occurred in these sea runs since the fish appeared to fast during their entire stream residence, about 287 days (Table 2). Weight loss during this 8- to 9-month fast was very marked (157.58 ± 15.80 g), a loss nearly equivalent to the amount gained during time at sea.

Mortality was high among spawning Dolly Varden, but, unlike the Pacific salmon, about 50%

*Personal communication with John Isakson, Fisheries Research Institute, University of Washington, Seattle, 1973.

Fig. 5—Downstream migration patterns of Dolly Varden and silver salmon smolts from a fish trap in Midden Cove Stream, 1971. N is the total number of fish.

Fig. 6—Growth of anadromous Dolly Varden from Bridge Creek.

Table 2—Average Weight and Length Changes in Anadromous Dolly Varden During Residence at Sea and in Freshwater*

Mean time spent, days	Mean wet-weight change, g/fish	Mean standard-length change, mm/fish
At sea		
73.45 ± 13.47	+182.08 ± 12.01	+26.64 ± 13.02
In stream		
286.50 ± 8.53	-157.58 ± 15.80	+4.15 ± 1.59

*Statistics given here and elsewhere in this chapter are for 95% confidence limits. The data given here are from fish captured in Midden Cove Stream, Amchitka.

Fig. 7—Upstream migration patterns of adult Dolly Varden, pink salmon, and silver salmon from Midden Cove Stream, 1971. N is the total number of fish.

of these adults survived to descend seaward in June with the smolts (Fig. 5). Char on Amchitka were found ascending to spawn for a third time in a 3-year period.

The life history of the landlocked char is similar to that of the sea-run form. Both forms mature at 3 or 4 years of age, but the landlocked fish have to rely on the scant food supply of the island streams. As a result, growth rate and fecundity of the two differ considerably (Fig. 8).

Fig. 8—Fecundity of anadromous and landlocked Dolly Varden from Amchitka. N is the sample size and $\bar{x}$ is the sample mean.

Threespine Stickleback. As was the case with the Dolly Varden, two morphologically and behaviorally distinct forms of threespine stickleback were found on Amchitka (Valdez and Helm, 1971). Unlike the two forms of Dolly Varden, these are distinct enough to be considered subspecies (Miller and Hubbs, 1969) or perhaps even separate species (Hagen, 1967). The first and most common inhabits freshwater ponds and streams. It differs from the second, a marine form, in that it possesses fewer lateral plates on the body. The freshwater form of threespine stickleback on Amchitka had an average of 5.6 plates, and the marine form, an average of 30.1 plates. The marine form also exhibited a lateral, horizontal keel on the caudal peduncle. This form was occasionally encountered in the quiet sheltered coves of the intertidal zone around the island and was also found in freshwater streams in June and July during spawning.

The freshwater form was encountered in over 80% of the ponds sampled, most of which were in the southeastern lowlands, but in only about 25% of the perennial streams sampled island-wide. Noticeably fewer sticklebacks were found in the northwestern highland landlocked ponds and the steeper gradient streams. This species is not adapted to a fast-flowing stream habitat, and, presumably, the nature of these streams hinders its distribution into the highland ponds.

Threespine sticklebacks on Amchitka exhibited sexual dimorphism. Spawning males could be distinguished from females by their bright nuptial colors; a brilliant red-orange abdomen, dark blue-green back, and a conspicuous turquoise iris. Females lacked nuptial coloration but exhibited abdomens distended from developing ovaries. Sticklebacks spawned on Amchitka in late May and early June. The number of eggs for all sizes of females was 123 ± 33 .

Males construct small nests of detritus and sand held together by a sticky kidney secretion. The female is enticed to the nest where she deposits the eggs, which are then fertilized by the male (Tinbergen, 1952). The young usually appeared along the shallow shorelines of Amchitka ponds by mid to late summer. These fish averaged 40 mm total length at the end of their first summer of growth, 52 mm at the end of their second summer, and 72 mm at the end of their third summer of life. These fish matured as 1-year olds (age group I) and usually spawned for only two seasons. Life expectancy for sticklebacks on Amchitka was 3 years (age group II), although a few survived into their fourth summer.

The diet of threespine sticklebacks on Amchitka, by percent composition, was approximately as follows (Valdez and Helm, 1971): zooplankton, 26%; immature insects, 25%; crustaceans, 18%; annelids and nematodes, 13%; miscellaneous, 18%. Since the threespine stickleback was numerous on Amchitka, it was considered a very important secondary consumer.

A high incidence of *Schistocephalous solidus*, a parasitic tapeworm, was found in pond sticklebacks (Valdez and Helm, 1974). The first larval stage was associated with a cyclops copepod and the second, or plerocercoid stage, with the body cavity of the sticklebacks. The host of the adult parasite was a piscivorous bird. Twenty-two percent of the sticklebacks examined from ponds and streams were infested with this cestode. A second macroparasite encountered in sticklebacks was the copepod *Thersitina gasterostei*. It occurred in the gill region and opercles of 21% of the fish examined. Neither parasite was suspected of imposing severe mortalities on the population in-

fested, although these hindered swimming of some individuals and may have enhanced predation by piscivorous birds and Dolly Varden.

Pink Salmon. The pink, or humpback salmon, is the most abundant and widely distributed of the three Pacific salmon species on Amchitka. The pink salmon has a 2-year life cycle, of which only the egg and fry stages are spent in freshwater

streams. Marine residence is usually about 16 months, followed by ascent of a stream to spawn. The even- and odd-year spawners are not related nor are their abundances and spawning successes.

Spawning adults were encountered in as many as 21 streams in 1970 and as few as 2 streams in 1973 (Table 3). Total estimated numbers of adults for the first 3 years of the survey were 674, 100, and 743, based on 8, 15, and 13 visits, respectively,

Table 3—Estimates of Adult Pink Salmon in Amchitka Streams*

Number†	Map†	Name and outlet coordinates	Estimate of adult pink salmon‡				
			1970	1971	1972	1973	1974
2023 I	NE	Roller Coaster Stream 636-972	10	0	10	0	10
2023 I	NW	Clevenger Creek 510-968	12	0	12	0	13
2023 I	NW	Duck Cove Stream 504-979	6	0	0	0	0
2023 I	NW	Silver Salmon Stream 546-993	30	0	0	0	0
2023 I	NW	Clevenger Lake Outlet 552-946	25	0	0	0	0
2023 I	NW	Bridge Creek 522-021	15	0	0	0	4
2023 I	NW	Ultra Creek 465-001	12	0	2	-	0
2023 I	NW	Stream BR 442-021	10	0	0	-	0
2024 III	SE	Teal Creek 427-037	6	0	10	-	2
2024 III	SE	Limpet Creek 367-099	6	0	15	-	10
2024 III	NE	Stream 356-115	6	0	0	-	0
2024 III	NW	Chapel Cove Stream 281-220	50	0	15	0	5
2024 III	NW	North of Chapel Cove 270-205	5	0	7	0	-
2024 III	NW	Midden Cove Stream 234-208	300	80	600	4	175
2024 III	NW	Burr House Cove Creek (south) 206-218	20	0	0	-	5
2024 III	NW	Burr House Cove Creek (north) 200-216	30	5	12	-	5
2024 III	NW	Fumarole Cove Stream 316-136	35	15	35	1	20
2024 III	NW	White House Cove Stream 303-148	6	0	5	-	0
2024 III	NW	Sandy Cove Stream 273-159	60	0	20	0	10
2024 III	NW	Signal Cove Stream (south) 224-165	5	0	0	-	2
2024 III	NW	Signal Cove Stream (north) 222-168	25	0§	0	-	2
Total			674	100	743	5	263

*The locations of these streams are shown in Fig. 1.

†Refers to U. S. Army Corps of Engineers maps of the Rat Islands A-3 NE, Alaska, Aleutian Islands (Amchitka Island).

‡A dash indicates that the stream was not visited that year.

§Three redds were found in September.

to each stream via helicopter, Snow-Trac, or on foot. The estimates of 5 and 263 for 1973 and 1974, respectively, are based on either 1, 2, or 3 visits to each stream via Snow-Trac or on foot. The frequency of visits to these streams was greatly reduced from the first 3 years because of the absence of a helicopter. A cyclic abundance is indicated, with greater numbers of adults returning in even years.

The distribution of spawning pink salmon on Amchitka was restricted by gravel dikes, impassable waterfalls, or inadequate stream flow. The larger runs were usually into highland streams, especially those flowing into Midden Cove, Sandy Cove, Fumarole Cove, Burr House Cove, and Chapel Cove (Fig. 1). The distinguishing features of all these streams were accessible outlets, deep resting pools, and an abundance of clean silt-free gravel.

Runs into the lowland streams, such as Bridge Creek, Clevenger Creek, Silver Salmon Stream, Roller Coaster Stream, and Ultra Creek (Fig. 1), were smaller and appeared to be restricted in size by the sparsity of clean gravel upstream from the outlets. Adult pink salmon using these lowland streams often spawned very near the outlets.

Pink salmon spawned in Amchitka streams in late August and early September in water ranging in daytime temperature from 7 to 9°C. Nearly all spawning occurred in or near the faster and deeper riffles, i.e., those sections with average flow of 1.0 m/sec. Preferred substrate for redds was gravel ranging from 1 to 7 cm in diameter, but eggs were often deposited among rubble 15 to 25 cm in diameter, particularly in the high intertidal zone.

An average of 1839 eggs per gravid female (range, 1441 to 2163) was estimated volumetrically from adult females of Amchitka. The young salmon usually hatched in November (77 to 88 days after spawning) at water temperatures of 2.3 to 3.5°C. The newly hatched sac fry were about 23 mm in total length. These young fish remained in the gravel redds until their yolk sacs were nearly absorbed in late March. Seaward descent began immediately after absorption but was observed as late as early June. Descending fry were about 32 mm in total length.

No observations of movement of Amchitka pink salmon in the intertidal zone or at sea were made. Presumably, the fingerlings first fed in the intertidal zone and then moved away from shore. These stocks spent between 14 and 17 months at sea before returning to the streams in August and September. Until about a week before their ascent, the adults continued to feed on a variety of intertidal crustaceans and small fishes, principally Pacific sandlances (*Ammodytes hexapterus*), vari-

ous marine sculpins (Cottidae), and unidentified crab megalops.

Returning adults were usually smaller than those of the Alaska mainland.* Females on Amchitka were smaller than males during the 3 years of greatest abundance (1970, 1972, and 1974) and larger the year of the smallest run (1971) (Table 4). So few fish were sampled in 1973 that adequate data could not be taken.

Table 4—Average Lengths and Weights of Adult Pink Salmon (Before Spawning) from Amchitka Streams

	1970	1971	1972	1973	1974
Sample Size					
Males	12	48	35	0	11
Females	10	37	29	1	12
Total	22	85	64	1	23
Mean Total Length, cm					
Males	52.8	51.1	52.9		54.2
Females	48.4	51.5	51.0	53.2	52.8
Total	50.2	51.3	52.0	53.2	53.5
Mean Wet Weight, kg					
Males	1.45	1.27	1.42		1.27
Females	1.15	1.35	1.30	1.51	1.47
Total	1.31	1.30	1.37	1.51	1.36

Silver Salmon. Silver salmon were considerably less abundant and more restricted in distribution than pink salmon. Juveniles of this species were found in five streams, although adults were encountered in only four. The rarity of juveniles and adults in three of these streams indicates that only Silver Salmon Stream and Midden Cove Stream were traditional spawning sites.

Adults ascended these streams from mid-September to early October. In the Silver Salmon drainage, these salmon entered the lake through a short stream about 100 m long (Silver Salmon Stream). The exact location of spawning was not known but was suspected to be in the small streams that drain into Silver Salmon Lake. Juvenile silver salmon abounded in this lake, where they fed primarily on chironomids, an assortment of zooplankton, and, occasionally, on small three-spine sticklebacks. A major descent of the smolts occurred in early to mid-July.

*Personal communication with T. R. Merrell, National Marine Fisheries Service, Auke Bay, Alaska, September 1971.

The location of spawning by silver salmon in Midden Cove Stream was also not known. Juveniles were numerous in the deep pools near the outlet, where they fed heavily on immature chironomids and ephemeropterans.

Most of the young fish became smolts after about 30 months of age (age groups II and III). About 82% of the smolts passing through a fish weir in Midden Cove stream belonged to these groups and about 18% belonged to age group I (Fig. 4). Young silver salmon were frequently observed near stream mouths and intertidally as though they fed there and returned to the stream periodically before becoming true smolts. This phenomenon was also noted with Dolly Varden. The major descent by silver salmon smolts occurred in June and July (Fig. 5), at which time these smolts were accompanied by descending Dolly Varden smolts and some adults.

All the adult silver salmon sampled were about 45 months of age (age group III). These returned 1 year before most mature silver salmon on the mainland; so they tended to be small (Table 5). However, too few adults were sampled to allow accurate estimation of their age structure.

Table 5—Average Lengths and Weights of Adult Silver Salmon (Before Spawning) from Silver Salmon Stream (1970) and Midden Cove Stream (1971)

	Sample size		Mean total length, cm		Mean wet weight, kg	
	1970	1971	1970	1971	1970	1971
Males	6	2	58.6	60.3	2.31	2.70
Females	1	0	59.8		2.41	
Total	7	2	59.6	60.3	2.33	2.70

Sockeye Salmon. The only other species of salmon found on Amchitka was the sockeye, or red, salmon. Only immature fish, in their fourth year of life, were found in the Silver Salmon drainage and intertidally in Constantine Harbor. It is believed that these fish strayed onto Amchitka from stocks feeding off the coast.

Coast-Range Sculpin. The coast-range sculpin was abundant only in Jones Creek and rare in two other lowland streams (Bridge Creek and Ultra Creek) and two unnamed phytogenic ponds in the Bridge Creek drainage. This species lived sympatrically with Dolly Varden and threespine sticklebacks in all waters where they were encountered. Its bottom-dwelling habit and small size made this species difficult to collect with electrofishing gear and seines.

COMPARTMENTAL STREAM MODEL

Since the main focus of this study was to evaluate the effects of unnatural perturbations on the freshwaters of Amchitka, the ecosystems had to be examined in detail. It would be futile to document the dynamics of all ponds and streams that might be affected by these perturbations. So a stream ecosystem of the type most likely to be affected by test activities was selected, and the components and rates within this system were quantified.

The product of this effort was a compartmental representation of Bridge Creek, a representative lowland stream on Amchitka. This stream is located in the southeastern region of the island, where the two nuclear tests were conducted. Although most of the data for this model were gathered from Bridge Creek, other streams were examined, and from them additional data were collected and inferences drawn to aid the development of this model as well as to define differences in the stream ecosystems.

Unfortunately the model was not refined sufficiently enough to yield all the mathematical functions defining the intercomponent relationships. Nevertheless, this compartmental representation was valuable in leading to an understanding of the dynamics of the stream and of how feedback of both subtle and drastic effects can affect the various components. For example, if the ground motion and pressure pulse of the underground devices affected only one species of macroinvertebrate, it would be essential to know how marked the impact on the population would be and how greatly this would affect sympatric species.

The compartmental model was designed as a series of boxes representing the components of the freshwater ecosystem (Fig. 9). Circles are used to represent the components of the marine ecosystem. The sizes of these boxes and circles are not intended to represent importance or relative mass of any component in the system. These components are joined by arrows that represent quantified relationships. The average dry-weight standing crop of the consumer organisms, expressed as grams per square meter of stream substrate, is indicated in each block. The flow of energy, expressed as kilocalories per square meter of stream substrate per year, is indicated by an arrow from one component to another.

Production of primary and secondary consumers, the macroinvertebrates and fishes, was computed by the instantaneous growth method:

$$P = G\bar{B}$$

Fig. 9—Compartmental model of the principal food web in Bridge Creek. Estimates of energy input, I , to each trophic level (1, 2, or 3) and production values for adult and juvenile Dolly Varden are in kilocalories per square meter per year. Values in each block represent mean standing crop in grams dry weight per square meter. G is the monthly instantaneous growth rate.

where P is the production in wet weight per unit time, G is the instantaneous growth rate, and $\bar{B}$ is the average stock biomass. Ricker (1958) and Chapman (1968) discussed this method as it applies to estimating fish production, and Waters and Crawford (1973) used it to determine production of macroinvertebrates. The wet weight of macroinvertebrates and fishes was used to compute production, and this value was later converted to dry weight by a constant of about 0.28. G , in the above equation, is used to describe the exponential growth of an organism and is defined as

$$G = \frac{\ln w_2 - \ln w_1}{\Delta t}$$

where w_1 and w_2 are the average weights of organisms at the beginning and end, respectively, of time Δt .

Primary Production

Primary production is the amount of organic substance assimilated by photosynthetic and

chemosynthetic activity of producer organisms (chiefly green plants). In streams on Amchitka the two principal components responsible for this assimilation are vascular plants and periphyton, an array of minute diatoms and algae attached to underwater substrates. The organic matter washed into or through the lotic system in the form of dissolved organic carbon and detritus is also a significant energy base. The suspended or planktonic life forms, which are important primary producers in ponds and lakes, are a rare and insignificant component of the streams.

Available solar radiation on Amchitka is low when compared with that on most land masses of similar latitude, probably because of persistent cloud cover. By using average daily measures of solar radiation on the island, Armstrong (personal communication) calculated an average yearly total of about $74 \text{ kcal cm}^{-2} \text{ year}^{-1}$. In contrast, the average yearly total at Seattle, Wash., was $110 \text{ kcal cm}^{-2} \text{ year}^{-1}$. Solar radiation became the starting point of energy flow as represented in the compartmental model (Fig. 9).

Periphyton. Production by periphyton in Bridge Creek was estimated by extracting chlorophyll *a* from periphyton growing on artificial substrates (Beers and Neuhold, 1968). The average monthly rates of this production in Bridge Creek varied from a high of $1.5 \text{ mg C m}^{-2} \text{ hr}^{-1}$ to a low of $0.3 \text{ mg C m}^{-2} \text{ hr}^{-1}$ (Fig. 10). The highest rates of energy storage by periphyton were observed in May, June, and July, and the lowest, from December to March. Integration of the curve in Fig. 10

Fig. 10—Rates of net primary production by periphyton in Bridge Creek during 1968. [From J. M. Neuhold, The Lowland Stream Ecosystem of Amchitka Island, Alaska, *BioScience*, 21(12): 684 (1971).]

yielded an approximation of net primary production by benthic periphyton of $3.9 \text{ g C m}^{-2} \text{ year}^{-1}$. This value was converted to kilocalories by multiplying it by a constant of 10.94 (Winberg, 1971). Estimated net primary production by benthic periphyton in Bridge Creek was $42.67 \text{ kcal m}^{-2} \text{ year}^{-1}$. This estimate is added to that derived for vascular plants before it is presented in the model.

Vascular Plants. Primary production by vascular plants was estimated by the harvest, or yield, method (Odum, 1971). The average monthly dry weight of plants in Bridge Creek was taken to yield an estimate of net production. It was assumed that there was little grazing on green vascular plants in the stream since all the resident fishes were carnivores and most of the macroinvertebrates were detritivores. Therefore any increase in the biomass of these perennials was interpreted as production.

The final estimate of annual net production, $20.36 \text{ g dry weight m}^{-2} \text{ year}^{-1}$, was multiplied by a constant of 0.45 to convert it to grams of carbon

and then by a constant of 10.94 to convert it to kilocalories (Winberg, 1971). This yielded an estimate of net production by vascular plants of $100.23 \text{ kcal m}^{-2} \text{ year}^{-1}$. Benthic periphyton production and aquatic vascular plant production were summed to yield an estimated total net primary production of $142.90 \text{ kcal m}^{-2} \text{ year}^{-1}$ (Fig. 9).

It is interesting to note that vascular plant production was nearly two and one-half times that of periphyton production. This is not too surprising considering that the heavy canopy of vascular plants in this stream shaded much of the predominantly mud substrate and probably retarded much of the periphyton growth.

Organic Carbon. The total organic-carbon content of water is composed of dissolved organic carbon and fine particulates, or detritus. This organic content is a measure of the organic enrichment of a stream. Production by aquatic organisms and the input of terrestrial organic matter (leaf litter etc.) contribute to this organic-carbon load in a stream.

In this analysis the dissolved organic carbon in Bridge Creek was measured by filtration of water samples to arrive at an estimate of detritus. Organic-carbon concentration appeared to be related to stream flow; a low concentration of $13 \text{ mg dry weight per liter}$ was measured in August, and a high of $19 \text{ mg dry weight per liter}$, in December and April (Neuhold, 1971). When integrated over the year, dissolved organic carbon was estimated at $870.0 \text{ g dry weight m}^{-2} \text{ year}^{-1}$. This value was then multiplied by a proportion of detritus to dissolved organic carbon and by a settling rate [both values determined from samples of water from Bridge Creek (Neuhold, 1971)] to yield an estimate of the detritus input into Bridge Creek.

Net energy input from this source was $4283.01 \text{ kcal m}^{-2} \text{ year}^{-1}$ (Fig. 9), a value nearly 30 times that of autochthonous primary production ($142.90 \text{ kcal m}^{-2} \text{ year}^{-1}$). Bridge Creek is evidently a heterotrophic system; it is dependent on the input of preformed organic matter from sources outside the stream, primarily twigs, roots, and leaves of tundra vegetation.

Secondary Production

The secondary producers (primary consumers) of Bridge Creek were dominated by a few species of macroinvertebrates, either detritivores or herbivores. The mean annual standing crop of these macroinvertebrates in Bridge Creek was $5.3 \text{ g dry weight/m}^2$; oligochaetes and immature chironomids made up about 73% of this biomass. Although the standing crop of oligochaetes (2.4 g/m^2) exceeded that of chironomids

(1.5 g/m^2), production by the latter ($29.0 \text{ g m}^{-2} \text{ year}^{-1}$) was the greatest of this trophic level. The immature insects of this system (chironomids, caddis flies, and mayflies) represented $32.6 \text{ g dry weight m}^{-2} \text{ year}^{-1}$ of production. The other significant contributors were oligochaetes and clams, which represented $9.1 \text{ g dry weight m}^{-2} \text{ year}^{-1}$.

These values of production were converted to kilocalories for use in the compartmental model by using the same constants (0.45 and 10.94) as those used previously for periphyton and vascular plants. Net production of macroinvertebrates, potentially available to secondary consumers, was $160.49 \text{ kcal m}^{-2} \text{ year}^{-1}$ from immature insects and $44.80 \text{ kcal m}^{-2} \text{ year}^{-1}$ from oligochaetes and clams, for a total of $205.29 \text{ kcal m}^{-2} \text{ year}^{-1}$ (Fig. 9).

Tertiary Production

The anadromous Dolly Varden (secondary consumers) dominated the fish fauna of Bridge Creek. Pink and silver salmon spawned in the gravel beds of the stream, but threespine sticklebacks and coast-range sculpin were rare.

In 1968 the average dry-weight standing crop of juvenile Dolly Varden (age groups 0, I, II, and III and a few of group IV) in Bridge Creek was an estimated 4.9 g/m^2 . Estimated production by these juveniles was $10.6 \text{ g m}^{-2} \text{ year}^{-1}$, or $52.18 \text{ kcal m}^{-2} \text{ year}^{-1}$ ($10.6 \times 0.45 \times 10.94$). Monthly instantaneous growth rate (G) for these fish was about 0.18.

The approximately 230 juveniles of age groups III and IV which descended seaward as smolts represented an estimated $4.21 \text{ kcal m}^{-2} \text{ year}^{-1}$ leaving the stream (Fig. 9).

Approximately 120 adult Dolly Varden that overwintered in Bridge Creek descended the stream from June to October 1971. These adults represented a total of about 21.79 kg wet weight or 6.10 kg dry weight. On the basis of a stream area of about 2210 m^2 , the biomass of descending adults was $2.76 \text{ g m}^{-2} \text{ year}^{-1}$, or about $13.61 \text{ kcal m}^{-2} \text{ year}^{-1}$ (Fig. 9).

The biomass of both smolts and adults descending Bridge Creek in 1971 represented about $17.82 \text{ kcal m}^{-2} \text{ year}^{-1}$. Data for this analysis were not available from 1968 because of failures in the downstream trap. The 1971 data, however, are probably representative of movement for any given year.

On the basis of the Dolly Varden tagged and released in Amchitka streams and subsequently captured, the average time spent at sea by these fish was 73 days. This residence usually extended from mid-July to late September. An average of 182 g wet weight per fish was assimilated during

this time since the fish fed voraciously on intertidal invertebrates and fishes. Monthly instantaneous growth rate (G) during this residence was 0.35, a much higher rate than that calculated for their residence in the stream ($G = 0.18$).

The return of Dolly Varden to Bridge Creek in August, September, and October 1971 was 114 fish. These represented about 69 kg of wet weight, over 20 kg of which was assimilated at sea. This high production of biomass should be recognized as having taken place in the marine rather than the freshwater ecosystem. The 69 kg represented $19.32 \text{ kg dry weight}$ or 8.74 g/m^2 of stream area. This was equivalent to $43.03 \text{ kcal m}^{-2} \text{ year}^{-1}$ (Fig. 9).

Production of adults overwintering in the stream was estimated as $-2 \text{ g dry weight m}^{-2} \text{ year}^{-1}$ (Fig. 9). Negative production in this case resulted from the fish's spending an average of 287 days in the stream with little or no feeding activity (Palmisano, 1971).

The deposition of gonadal products by Dolly Varden was quantified by taking mean gonadal weights for fish and multiplying these values by the number of adult spawners. Dry weights of gonadal products were determined and converted to kilocalories per square meter of stream. A total of $3 \text{ kcal m}^{-2} \text{ year}^{-1}$ of gonadal products was deposited by Dolly Varden in Bridge Creek (Fig. 9).

About 15 adult pink salmon ascended Bridge Creek in September 1968. This was equivalent to about $12 \text{ kcal m}^{-2} \text{ year}^{-1}$. These adults deposited an estimated 2 kcal/m^2 of gonadal products (ova and milt), including about 15,000 eggs. The mortality of both eggs and fry is usually high. The estimated total energy content of the surviving fry descending to sea in March 1969 (about 7 months after spawning by the parent stock) was only about 659 kcal, or 0.3 kcal/m^2 (Fig. 9).

Integration

The energy budget of Bridge Creek was strongly dependent on allochthonous organic matter and chironomid production (Fig. 9). Autochthonous production was low, probably because of the low level of available solar radiation and the low water temperatures.

Detritus and dissolved organic carbon contributed the greatest potential amount of basal energy into the system. The production of benthic periphyton was very low. Of the macroinvertebrates, the immature insects accounted for about 78% of the energy available to the next trophic level, the fishes. The immature midges were responsible for about 70% of the total production by macroinvertebrates.

Although adult Dolly Varden dominated the standing crop of secondary consumers in the stream, production by them was nil. In fact, food consumption was so low that production was calculated as negative; the fish sampled lost weight during the period observed.

The production of juvenile Dolly Varden in the stream resulted primarily from the consumption of large numbers of immature midges. As these fish became smolts and descended to sea, their consumption increased significantly, and their growth rate nearly doubled over that observed in the streams ($G = 0.35$ vs. 0.18). However, this accelerated growth lasted only about 73 days, at which time the newly mature fish joined the adults to ascend the stream and spawn. Feeding in the stream was almost nonexistent, and weight loss was great.

This exchange of energy between the freshwater and marine ecosystems demonstrates the importance of the latter to the survival of the Dolly Varden on Amchitka. Streams like Bridge Creek serve as a nursery to this species; only the juvenile fish feed actively in the stream. Once mature, these fish feed almost exclusively at sea and return to the stream only to spawn, but at the expense of great loss in weight.

The evolution of this stream system appears to be the most beneficial to the Dolly Varden as a whole since the food in the stream is too scant to support fish as large and voracious as the sea-run adults. This hypothesis is supported by the relatively small size of the adults of the landlocked Dolly Varden on Amchitka.

Streams of Amchitka like Bridge Creek support a lower number of faunal species with fewer individuals of each in comparison to mainland streams of similar latitude. This phenomenon of low species diversity of island ecosystems is well documented (Preston, 1962; MacArthur and Wilson, 1967). The idea of species diversity is introduced here because it appears to be a key factor in the dynamics of these insular streams and in how they respond to perturbations.

The information index (H) of Shannon and Weaver (1959) best quantifies the species diversity of communities (Margalef, 1968). The indexes of two Amchitka streams and a pond demonstrate this low diversity of macroinvertebrates in island communities (Table 6).

On the basis of such indexes, the resistance or tolerance of these communities to perturbations is expected to be low (Wilhm and Dorris, 1966). This is hypothesized whenever the energy web of a community is less than complex. A perturbation would more easily affect the community if one species is highly dependent on a very few other

species, i.e., if a predator has few alternative prey species.

Although most of the brood stocks of salmon and Dolly Varden on Amchitka feed at sea, survival of future generations is largely dependent on clean pollution-free stream gravel for spawning and on adequate food for juveniles in the stream. Since the juvenile Dolly Varden rely heavily on immature midges, this insect appears to be a key species to the survival of the population.

PERTURBATIONS

The most apparent effects of AEC project activities on the freshwaters of Amchitka resulted from construction of access roads, drilling of emplacement holes for the nuclear devices, and detonation of the two devices. More subtle effects were seen from a car wash, stream-channel alterations, and human sewage disposal.

Although most human activities were restricted to the southeastern end of the island and to the vicinities of the two test sites, many of the effects of road construction, borrow areas, and stream-channel alterations were widespread. The major problem from these activities was the introduction of foreign matter, such as suspended particulates (silt), organic wastes (sewage), or chemicals (drilling muds), into the streams and ponds.

The physical effects of the two detonations were restricted to the areas immediately around the test sites; some ponds were drained, and streams were altered by scarps and upheavals. Fish populations suffered most in those waters affected by physical changes.

The effects that were most difficult to evaluate were those associated with the leisure and recreational activities of the island personnel. Fishing was a favorite pastime on the island, and the attempts to "improve" this sport were common. Fish were frequently transferred into streams and ponds formerly lacking them by the personnel of this occupation and perhaps also by troops of the wartime occupation of 1943. Thus landlocked ponds in which no fish were expected often supported Dolly Varden with the morphological characteristics of the anadromous form. This was a puzzling phenomenon until this transfer of fish was recognized.

The meager runs of salmon on Amchitka also suffered from the occupation by modern man. Streams were too small to provide good cover for the adult fish to hide and escape fishermen armed with clubs and stones.

The effects of our investigation on these populations should also be recognized. Electro-fishing equipment, gill nets, trammel nets, and

Table 6—Species Diversity Indexes of Benthic Macroinvertebrate Fauna from Selected Ponds and Streams of Amchitka

Station	Invertebrate groups											Diversity index (H)	
	Chironomidae	Ephemeroptera	Trichoptera	Simuliidae	Nematoda	Oligochaeta	Pelecypoda	Amphipoda	Isopoda	Platyhelminthes	Arachnida		Ostracoda
Midden Cove Stream	X	X	X	X	X								0.375 ± 0.076
Bridge Creek	X	X	X		X	X	X			X	X	X	1.155 ± 0.093
Lake CO	X				X	X		X	X			X	1.071 ± 0.083

hoop nets were used to sample the population of fishes. Records were kept on all fish handled. We feel that we did not jeopardize the health of any fish populations on Amchitka, and we are confident that those fish we removed for examination were rapidly replaced through natural recruitment.

Road Construction

Silt from Roadways. Roads on Amchitka were constructed of crushed rock ranging in size from several centimeters to silt-size particles. Low rates of infiltration of rain into the roads resulted in the concentration of runoff water in the roadside ditches or down wheel ruts on hillsides. Rates of flow were sufficient to carry silt from the road into natural drainage channels. Erosion products from the road and graded ditches in the Bridge Creek drainage were deposited in a marsh downstream from the road. Not all the silt was trapped in the marsh, as indicated by the increased turbidity in the stream after just a moderate rain. Such siltation may have been a major factor in the sharp decline in the use of Bridge Creek as a spawning site by pink salmon (Table 3).

A roadside marsh and tundra area near Pratfall Lake also trapped silt carried from the main road. Silt carried through this area was deposited in the lake, changing the formerly firm bottom to a soft one. Silver Salmon Lake, downstream from Pratfall Lake, was similarly affected. Nearly all streams, where crossed by a road, showed evidence of siltation along stream banks and within the channel. These examples and others, such as Clevenger Creek, were particularly noticeable because of the studies conducted there.

A beneficial effect of roads resulted from the gravel foundation on which culvert pipes rested in streams (Bridge Creek, Clevenger Creek, Jones Creek, and Duck Cove Stream). The gravel spilled near the road culverts was very desirable for spawning by pink salmon and Dolly Varden.

Silt from Borrow Areas. Sites used as a source of rock for roads and other construction also contributed silt to nearby watercourses. Surface drainage from Galion Pit carried silt onto the tundra near Silver Salmon Stream. The tundra, however, was unable to absorb all the silt; thus there were high stream turbidities after rainstorms. This silt combined with that added from the road and resulted in heavy deposits in the upper end of Silver Salmon Lake. Siltation was noted in the fall of 1967 in White Alice Creek, south and east of site C, as well as in Silver Salmon Lake, Pratfall Lake, and Silver Salmon Stream between the two ponds. Additional siltation was noted in the upper Fumarole Cove drainage and also south and east of drill site F at the same time. In each of these cases, there was nearby construction activity involving the use of bulldozers to remove the vegetative mat and to shift soil and rocks.

Drilling

Sumps. Ponds with capacities of 40,000 to 50,000 or more barrels (1 barrel $\cong$ 45 gal) of liquid were constructed in close proximity to drilling sites to serve as sumps for drilling mud. The approximate composition of this drilling mud was 91 to 93% water and 6 to 8% oil with such additives as bentonite, lignite, cement, sodium bicarbonate, paper, and Q-BROXIN* (ferrochrome lignosulfonate) to maintain the desired viscosity and consistency. A pH range of 10 to 12 was attained with this mixture.

A bioassay was conducted to determine the toxicity of the supernatant liquid from a sump near site D. The liquid was taken from near the surface of mud ponds that had been undisturbed

*Q-BROXIN is a registered trademark of Georgia Pacific Corp.

for several months. It was highly turbid, containing an undetermined amount of fine suspended material. The 50-hr LC_{50} * for Dolly Varden was about 9%, and that for threespine sticklebacks was about 16%. This potentially hazardous mixture has been left in ponds with relatively fragile walls in this seismically active region. Failure of a pond wall or inundation of a low-lying pond could result in an extensive mortality of freshwater organisms in the receiving stream or pond.

Spills and Releases. Leaks or losses of drilling mud from holding ponds, or sumps, occurred at various times. These spills ranged from small intermittent flows to as much as 20,000 to 25,000 barrels. Small losses from the Milrow site into Clevenger Creek occurred in January 1968, and large spills occurred from mid-May to mid-June 1969. Similar, but more frequent, contamination of White Alice Creek, near the Cannikin site, occurred from summer 1968 until just before the Cannikin event of November 1971. These spills were a result of normal drilling operations, not event-induced ground motion.

The 1968 spills into Clevenger Creek resulted in modest reductions of Dolly Varden and macroinvertebrates, but the larger spills in 1969 eliminated virtually all life in the portion of stream receiving the toxic liquid (Fig. 11). Both branches of White Alice Creek, one northwest and the other southeast of the Cannikin site, were contaminated with frequent small spills. Larger spills in 1970 reduced both macroinvertebrate and fish populations to near zero downstream from sites of contamination. Although the populations of both fish and macroinvertebrates were completely eliminated by the spills, recovery was initiated by immigrants from unaffected areas.

In June, July, and August 1970, the mean flows of White Alice Creek at the U. S. Geological Survey gauging station were 0.027, 0.054, and 0.132 m^3/sec , respectively (U. S. Department of Interior, 1970). The gauging station is far downstream from the drill pad, and it measures flow derived from portions of the watershed downstream from site C as well as from the branches on each side of the site.

An inspection in June 1970 revealed that the bottom of White Alice Creek was covered with caked and peeling mud and silt, and the odor of oil was very apparent. Large sheets of old and used plastic were strewn along the stream and its banks. Two live fish were observed during an inspection of the entire length of the stream, but no fish were

captured by electrofishing in selected areas. No live macroinvertebrates were found.

In mid-July 1970 there was evidence of spills of supernatant liquid from five locations at site C. At least four of the five were intentional releases since two originated from drain pipes installed in sump walls and two others from trenches cut through these walls. One source was flowing about 0.0056 m^3/sec (0.2 ft^3/sec) during the time of inspection. Since the mean flow of White Alice Creek was 0.054 m^3/sec (1.92 ft^3/sec), the flow in one branch adjacent to the drill site was less than half this amount, or less than 0.027 m^3/sec . This resulted in a contaminant concentration of about 21%, a concentration demonstrated to be lethal to both Dolly Varden and threespine sticklebacks by use of bioassays. All fish downstream from the spill point were likely killed as a result of the toxic liquid. Evidence indicated that spills of similar or larger magnitude also occurred in the southeast branch of White Alice Creek.

At the time of the Milrow detonation, ground motion liberated much of the oily residue of the drilling mud that had been taken up by organic matter and vegetation in and along Clevenger Creek. With no new additions of this material, the stream populations gradually recovered (Fig. 11). Although the odor of oil was still apparent in late July 1970, pink salmon apparently spawned successfully near the mouth of this stream in August since adults appeared again in 1972. However, since these spawners could have strayed from some other stream, their presence was not absolute proof of successful spawning in 1970.

It appears that the spills of drilling mud into Clevenger Creek resulted in mortalities of aquatic organisms without any long-term effects on the habitat. Particulate material from the mud was gradually eliminated, and no additional mud escaped into the stream. White Alice Creek, in contrast, has been subjected to long periods of chronic pollution with little opportunity for particulate matter to be removed. Habitat alteration was more extensive in this situation, resulting in a long delay in recovery.

Although some drilling mud may have splashed out of holding ponds at the time of the Milrow test, cracking and failure of pond walls at site D during Cannikin were far more serious. Drilling-mud residue and silt from pond walls covered the bed and banks of Falls Creek. A subsequent intentional release of 20,000 to 25,000 barrels caused further damage to this stream.† Down-

*The concentration that is lethal to 50% of the sample after 50 hr of exposure.

†From field records of Baine Cater, U. S. Fish and Wildlife Service, Anchorage, Alaska, 1972.

Fig. 11—Population trends of 10 species of macroinvertebrates and of adult and juvenile Dolly Varden in Clevenger Stream before and after drilling-mud spills from the Milrow test site. The 95% confidence interval for each estimate is indicated for Dolly Varden.

stream, where colonization from an uncontaminated branch of the stream could occur, Dolly Varden and some macroinvertebrates (simuliids, chironomids, and trichopterans) were found. Absent, however, were the mayflies (ephemeropterans), whose presence is usually associated with clean well-aerated water. The upper portion of Falls Creek was devoid of fish and macroinvertebrates where heavy deposits of silt undoubtedly retarded their recovery.

Water Sources. Water for various drilling-related uses was pumped from ponds in the vicinity of each site. Pumps were powered by diesel engines. Frequent spillage of diesel fuel saturated the soil around the pump site and, in some cases, flowed or seeped into nearby ponds. These oil-soaked areas were slow to revegetate. In May 1968 dead Dolly Varden were collected from the water-source pond for the D drill site. Oil slicks were observed on that pond.

Miscellaneous

Off-Road Vehicle Traffic. One of the initial phases of test preparation was the placement of telemetric and control cables. Some of these cables were installed parallel to the main road from large tracked vehicles. Repeated crossing of marshy areas

adjacent to some ponds and streams damaged considerably the vegetative mat. Where such damage occurred between a road and a nearby pond, such as Pratfall Lake (Fig. 12), the capacity of the marshy tundra to filter silt from the road was greatly reduced. Runoff water threaded along and between ruts in the tundra, carrying silt into the nearby pond. Stream banks were similarly damaged, the ruts providing ready channels along which runoff water concentrated.

Slight depressions in the vegetative mat of Amchitka can be detected for years after a light tracked vehicle has passed. Heavy vehicles, or repeated use of the same trail, damaged the vegetative mat and thus exposed the soil beneath to pounding rain and wind. Such areas will probably remain in an altered condition for many years, although major drainage will likely remain unchanged.

Vehicle Washing. A car wash was constructed on the bank of a small stream flowing into Clevenger Lake. Water from this facility carrying dust, oil, and other debris flowed into the stream and thence down into the lake. There were no provisions to impound or otherwise retain the wash water to remove these materials before its release into the surface-drainage system. Silt and oil were

Fig. 12—Location of ponds and streams referred to in discussion of Milrow and Cannikin test-time effects.

readily apparent in the stream between the facility and Clevenger Lake.

Stream-Channel Alteration. A minimum of this type of very damaging activity was noted. A short section (about 50 m) of Bridge Creek, immediately upstream from the main road, was straightened to provide a more nearly perpendicular approach to the road and permit installation of a stream gauge. Damage was limited to loss of a very small portion of stream and some siltation downstream caused by the channeling. This activity by itself would be considered minor, but this silt was added to that washed in from the road and thus compounded an already serious problem.

An additional channel alteration occurred in the fall of 1970 at the Clevenger Lake outlet. Here the stream just above high-tide level was straightened and moved to permit construction of a boat-launching ramp. This activity occurred at a time when pink salmon redds were under observation; so a direct evaluation could be made. Fill placed in part of a very limited area used for spawning by salmon covered two redds and left two others stranded out of water. This was about 30% of the estimated pink salmon reproduction in this stream. Two years later, in 1972, when progeny from the 1970 run should have returned to spawn, no salmon were observed in this stream. A combination of habitat alteration, superimposed on excessive predation by island personnel, may have eliminated this particular run of salmon.

Sewage. *Sphaerotilus natans*, an indicator of organic pollution, was found in the outlet creek from Clevenger Lake in September 1967. Subsequent examinations in winter and spring failed to locate this bacterium, and none was observed in subsequent years.

Nuclear Detonations

Physical Effects. Severe ground motion at test time, both horizontal and vertical, caused some changes in the freshwater system. Test-generated forces raised the ground surface momentarily into a shallow dome-like shape within a radius of about 500 m (Milrow) to 1000 m (Cannikin). A collapse crater then formed as a shallow saucer-shaped depression within the area of uplift. Ponds situated within the uplifted area were tilted away from surface zero (SZ), and, if located within the crater area, they were tilted again, this time toward SZ. Three ponds, all within 500 m of SZ, were tilted and partially drained by the Milrow event (Fig. 12). A culvert, through which the outlet of Clam Lake flowed, was raised some 90 cm, raising the water level of the lake.

Cannikin uplifted a larger area and thus affected a greater number of ponds. Five ponds were drained by tilting and fissures created by uplifting and subsequent crater formation. There was no water in any of these ponds 1 year after Cannikin. Two of the five were known to have contained Dolly Varden, and two contained threespine sticklebacks. Fissures developed along banks or in basins of a few additional ponds, but these were not drained. The banks of a few ponds also sloughed during the detonation.

The flow of several streams was affected by both Milrow and Cannikin. Sloughing banks filled some sections of the channel in Clevenger Creek after Milrow, reducing the amount of Dolly Varden habitat. Undercut banks, which provided desirable hiding areas for Dolly Varden, appeared most susceptible to collapse. Not only was this cover eliminated but also part of the channel was occupied by the collapsed bank, reducing the amount of living space. Similar effects were noted on other streams near Milrow. Cannikin produced similar, but more extensive and severe, stream bank and hillside sloughing; a portion of White Alice Creek was dammed by a large slide.

Small portions of bank can be expected to collapse during natural seismic activity, and tundra is known to creep downhill as a result of natural events (Everett, 1968). Milrow and Cannikin telescoped such infrequent and long-term events into a short time span. Although the phenomenon of slides and bank collapse is natural, the rate at which they occurred is not; so these effects induced by testing are far more severe than normal landform changes.

The most dramatic physical effect of Cannikin on the freshwater ecosystems was the nearly complete interruption of flow in lower White Alice Creek, an interruption that lasted for slightly more than a year. Runoff from the upper White Alice Creek drainage flowed into the subsidence crater just east of Cannikin SZ and thence into the rubble chimney beneath the crater. By about Nov. 30, 1972, nearly 13 months after the detonation, the chimney and the subsidence basin had filled, forming Cannikin Lake (Gonzalez et al., 1974). An outlet then formed, restoring the flow in the lower reaches of the stream. The dimensions of the new lake and the development of freshwater biota in it are discussed in Chaps. 3 and 13, respectively.

The section of lower White Alice Creek in which flow was interrupted is about 1000 m long; whatever fish and macroinvertebrate populations this section supported before the interruption were presumably lost. However, the populations of both of the life-forms began recovery as soon as migrants from unaffected areas of the stream gained

access with the reestablishment of flow. Numerous small pools, apparently replenished by small springs and subterranean flow, were a main refuge for life-forms when the stream was low.

Most of the macroinvertebrates were immature forms of aerial insects. Brood stocks gained access by drifting from upstream areas and by flying, as adults, from adjacent streams. The Dolly Varden also gained access by drifting downstream and by swimming upstream from unaffected areas of the stream and from ponds in the drainage. These populations later became the source of fish for the newly formed Cannikin Lake. It was later learned that local sportsmen supplemented this population with Dolly Varden by transferring them from other ponds on the island.

Biological Effects: Milrow. Direct biological effects of testing were limited, both in terms of the number of populations affected and the area over which the effects were detectable. Three of the ponds closest to Milrow SZ did not contain any fish. Dead threespine sticklebacks were found in two ponds near SZ, on the shore and bottom of Lake AM (686 to 930 m from SZ) and in Clam Lake (503 to 677 m from SZ) (Fig. 12). Clam Lake contained Dolly Varden, but none were affected by the blast. An examination of 30 dead sticklebacks from these two ponds revealed that 27 of them had ruptured air bladders, internal hemorrhaging, and pale gill filaments. Dead sticklebacks were also found on the shore of a pond 1145 to 1320 m from SZ (Lake CF). These fish appeared to have been stranded on the tundra after being washed ashore by ground motion. No internal injuries were noted in any of these, nor were there any dead fish on the lake bottom. For a clearer definition of the zone of shock effect, it is noted that threespine sticklebacks were killed in Clam Lake and Lake AM up to 930 m from SZ, but no dead fish were found in Pratfall Lake or a small pond across the road from it (1040 m from SZ) and no fish were killed in pond CF (1145 m from SZ). Thus the outer limit of lethal effects from Milrow was between 930 and 1040 m from SZ.

It is estimated that about 85% of the threespine sticklebacks in Clam Lake, perhaps as many as 40 to 50% of those in Lake AM, and a negligible percentage of those in other ponds were killed as a direct result of the test. No dead Dolly Varden were found.

Increased water depth in Clam Lake precluded further quantitative sampling with a seine to evaluate changes in the stickleback population after Milrow. However, minnow traps indicated that reproduction occurred in all years after the Milrow event. Seining in Lake AM indicated that

the stickleback population there had also recovered, with successful reproduction occurring each year.

Biological Effects: Cannikin. Cannikin produced a greater number of fish casualties than Milrow. The majority of them were the result of the destruction of habitat rather than direct effects on fish. An estimated 7700 fishes, including 670 Dolly Varden and 7030 threespine sticklebacks, were killed when four ponds were drained (BO, DF, DH, and a small pump pond, Fig. 12). About 2900 threespine sticklebacks were killed by rapid pressure change in three ponds, DK, DM, and DN, and 70 sticklebacks were thrown clear of the water and stranded on the banks of ponds DL, DM, and DN (Fig. 12). An additional 30 Dolly Varden were similarly stranded on the bank of pond DH before it drained after the formation of the collapse crater. The distribution and estimated numbers of fish killed by the Cannikin detonation are given in Table 7. Results of test-time experiments with live-boxes and salmon eggs in artificial redds are given in a compilation of immediate test effects by Kirkwood and Fuller (1972).

Summary of Effects

The impact of some AEC activities on the freshwaters of Amchitka will remain in evidence for decades. The ponds and streams drained or altered by the scarps, upheavals, and crater basins will probably never return to their former state. Most of those areas which were exposed to the more subtle effects of the car wash, stream-channel alteration, and sewage disposal exhibited evidence of recovery shortly after the stress was removed.

The main unpaved road, constructed by the military forces in 1943, was left intact on the island after the AEC occupation. It was extensively improved for travel by the AEC, and the siltation that resulted from the frequent addition of gravel and from maintenance with road graders reached many streams and ponds. The volume of motorized traffic on this road added to the problem. The flushing action in streams may eventually transport most of this silt to sea, but much of it appears to have compacted and may remain for many years. This silt has most significantly affected spawning sites for fish and the survival of macroinvertebrates. Some additional roads were constructed by the AEC to the test sites. These and the main road will likely stabilize in the absence of extensive use and contribute little additional silt except during heavy runoff of water.

All the drilling mud from the Milrow emplacement shaft was eventually disposed of into Clevenger Creek. The biota of the stream suffered

Table 7—Estimated Mortality* of Freshwater Fishes in Ponds Affected by the Cannikin Event on Amchitka (Nov. 6, 1971)

Station	Distance from SZ, m	Pond drained	Threespine stickleback			Dolly Varden		
			Preevent population	Number killed	Percent killed	Preevent population	Number killed	Percent killed
BO	810	X	2,030	2,030	100	300	300	100
DF	1,000	X	5,000	5,000	100	0	0	
DH	940	X	0	0		300	300†	100
DK	1,210		13,500	2,000	15	200	0	0
DL	1,350		325	15	5	0	0	
DM	1,520		2,000	65	3	0	0	
DN	1,800		11,000	890	8	‡	0	
Pump Pond	380	X§	0	0		300	100	33

*All preevent population estimates were obtained by mark and recapture or seining methods. Where a pond was completely drained, the entire population was eliminated. In those ponds where only part of the fish were killed, the loss was determined either as a finite number of fish or as a percentage of the original value.

†Thirty of these fish died when they were tossed on shore by the blast.

‡No preevent estimate was available.

§The pump pond was partially drained.

extensively from this toxic fluid, but a nearly full recovery of fishes and macroinvertebrates was observed about 5 years after the spills.

The drilling mud that reached White Alice Creek before the Cannikin detonation also decimated the fish and macroinvertebrate populations. The stream slowly began to recover as this pollution ceased, but, after the Cannikin blast, a lake formed which flooded most of this polluted section of stream. Dolly Varden were numerous in the lake, and the density of macroinvertebrates was increasing about 2 years after its formation. Drilling mud remained in two of the four main sumps of the Cannikin site after the operation was completed. Since the material in the sumps could escape into the lake, the threat that drilling mud might reach the White Alice watershed remains.

Two additional large sumps filled with drilling mud were left at site D in the central region of the island. The walls of these sumps were very unstable in 1974, and the contents of these pose a definite threat to the stream and possibly to the intertidal zone below the site.

None of the populations of fishes were permanently affected by the Milrow detonation. The populations of sticklebacks in those ponds subjected to lethal pressure waves were able to recover since enough fish survived to repopulate. Those ponds which were drained by ground motion did not originally support fish.

The four ponds drained by the Cannikin blast will probably not refill to support the former populations of Dolly Varden and threespine sticklebacks. Populations in those ponds tilted or

partially drained are expected to recover as did those affected by Milrow.

Although some fish populations near test sites and areas of intensive construction activity may not recover, the overall adverse effects of the AEC occupation of the freshwaters were not widespread or permanent. Most fish populations were undisturbed, and those which experienced adverse effects should eventually recover.

SUMMARY

The landscape of Amchitka is dotted with an abundance of small shallow ponds, many connected and drained by small or intermittent streams. As the streams approach the seacoast, the valleys widen. Most streams flow gently into the sea, but many spill precipitously over sea cliffs.

These waters support six species of freshwater and anadromous fishes. Dolly Varden and threespine stickleback are the most abundant and widespread. Small numbers of pink and silver salmon use the streams for spawning; coast-range sculpin are restricted in distribution; and sockeye salmon are rare. None of the six species occur in numbers great enough to constitute commercial importance, although Dolly Varden were sought extensively by sports fishermen with the recent AEC occupation.

These fishes are highly dependent on small crustaceans and immature insects for their food source. A low diversity of these macroinvertebrates dominates the primary consumer level of the freshwaters. Piscivory is rare except by Dolly

Varden living sympatrically with threespine sticklebacks in ponds.

A compartmental model of a representative stream on Amchitka illustrates that these systems are not highly productive ones. The majority of the basal energy supply is allochthonous, entering the streams as dissolved organic carbon and as detritus. This model also illustrates the great dependence of juvenile anadromous Dolly Varden on immature insects, especially chironomids. The adults of this fish species feed primarily at sea and use the streams as spawning sites. Thus the streams with access to anadromous fish function mainly as nurseries for their young.

The effects of the AEC activities on the freshwaters were limited to the areas near the two test sites and to those areas of greatest activity, i.e., adjacent to roadways and encampments. Long-lasting deleterious effects were primarily from habitat alteration, either during excavation of roads or building sites or during the nuclear tests themselves.

The compartmental model indicated that the freshwater stream ecosystems are very sensitive in one area. The health of the fish populations is highly dependent on the condition of the macroinvertebrates, especially chironomids. A most marked effect was seen on both fishes and macroinvertebrates when toxic drilling muds were released or spilled into streams and ponds. Although most fluid was toxic to both forms of life, the effects lasted beyond its presence because the macroinvertebrates were unable to recover from the smothering effects of the compacted material left on the stream bottom. The populations of fishes were also depressed because of the absence of food organisms in spite of clean flowing water. The rapid flushing of these streams eventually removed the toxic muds, allowing the macroinvertebrates to regain access. The fish populations soon recovered also. The recovery of both populations was dependent on the presence of brood stocks in unaffected areas of the watershed.

The freshwaters of the island, as a whole, were not deleteriously affected. The populations of fishes and invertebrates in those waters subjected to subtle perturbations and where there were no physical habitat changes are expected to eventually recover to their original state.

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Fishery Resources of the Western Aleutians

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The fishery resources in the western Aleutian Islands are diverse, abundant, and heavily exploited, primarily by Japanese and Soviet fishermen. Seven groups make up the bulk of the current catch: salmon (sockeye, chum, and pink), king crabs, Pacific halibut, Pacific ocean perch, sablefish, walleye pollock, and Pacific cod. Three species of whales (sperm, fin, and sei) are also captured. The marine environment is highly productive and is relatively unaffected by man's activities other than fishing.

Prospects for continued or expanded fishery harvests vary according to species. Pink and chum salmon stocks will probably remain at about current levels. Sockeye stocks

will probably recover somewhat from their present low levels if average environmental conditions prevail and international regulations are successful in controlling the high-seas catch. King crab harvests by U. S. fishermen should gradually increase as previously unexploited stocks are fished. Pacific halibut, sablefish, and Pacific ocean perch stocks and catches will probably continue at current low levels. Walleye pollock and Pacific cod catches will probably increase somewhat. Whale stocks will continue their precipitous decline, and their harvest will probably end within a few years as a consequence of conservation efforts and international treaties.

The fishery resources around Amchitka Island are abundant and diverse, but until recently man has used them to only a limited extent. Although the original Aleut inhabitants of Amchitka depended on the sea for most of their food, they had little impact on the fish stocks because fishing methods were primitive. Their refuse middens, formed during several milleniums of continuous occupation, consist almost entirely of the skeletal remains of marine fishes, mammals, and invertebrates (Desautels et al., 1970). The size of the original Aleut population is unknown, but all estimates are over 10,000, and nearly all the Aleutian Islands were inhabited; on Amchitka alone, 73 separate occupation sites have been identified (McCartney, Chap. 5, this volume). After the Aleutians were discovered by the Western World in the eighteenth century, the Aleut population dwindled to less than 1000 for the entire Aleutian chain. As a result, for the 100-year period between the mid-nineteenth and the mid-twentieth centuries, the fishery resources were disturbed very little by man.

In the 1950s fish stocks in the western Aleutians were exploited on a large scale on offshore or deepwater species that had not been available to the Aleuts. In 1952 Japan expanded the scope of its high-seas gill-net fishing for salmon, *Oncorhynchus* spp., from Asian waters to the western Aleutians, and in the early 1960s Japan and the Soviet Union sent enormous fleets of trawlers to

the western Aleutians to fish virgin stocks of Pacific ocean perch, *Sebastes alutus*. During this same period both nations expanded their whaling fleets throughout the North Pacific Ocean.

Soviet or Japanese trawlers were frequently observed fishing off Amchitka during the Atomic Energy Commission (AEC) occupation of the island. Direct evidence of the magnitude of these Japanese and Soviet fisheries is the tremendous accumulation of derelict fishing gear on Amchitka's beaches (Fig. 1). In 1972 I surveyed 10,000 m (33,000 ft) of these beaches to provide a basis for estimating the total amount of fishing debris on the island. I estimated that at least 22,000 items made of synthetic materials were on the island beaches, including nearly 12 tons of discarded scraps of trawl web and 6600 salmon gill-net floats (Anonymous, 1973).

By 1971 the Soviet and Japanese fishing effort in the western Aleutians had declined, and only the Japanese high-seas salmon gill-net fishery was continuing at a level of effort comparable to the peak years in the 1960s. The stocks of Pacific ocean perch and whales had been so diminished by intensive fishing that they could no longer support the previous high levels of effort.

Although this relatively low fishing effort is continuing, the basic productivity of the seas in the western Aleutians is unimpaired, and it seems inevitable that additional species as well as remnant

Fig. 1—Japanese salmon gill-net fragment washed up on Amchitka Island beach.

or recovered stocks of previously fished species will again be exploited.

The fishery resources in the western Aleutians are now used only by Japan, the Soviet Union, and the United States. Other nations, however, may soon begin fishing there. South Korea has already done some exploratory fishing, and Poland, North Korea, West Germany, and the People's Republic of China have expressed interest in fishing in the area.

United States fisheries in the western Aleutians have been for Pacific halibut and crab, which have a high unit value. These U. S. fisheries have been far exceeded in intensity, total value, and geographic extent by the fisheries of Japan (Fig. 2) and the U.S.S.R. (Fig. 3), which concentrate on species with a low unit value. In 1972, for example, over 1300 Japanese and Soviet vessels were employed in fisheries off Alaska's coast (National Marine Fisheries Service, 1973). The situation is changing, however, because the target species sought by the foreign trawl fleets are being depleted and U. S. fishing is expanding to include previously unexploited crab stocks in the western Aleutians. Furthermore, as a result of changing economics and regulations, the U. S. fishing industry is exploring the feasibility of trawling on

Alaska's continental shelf in competition with the foreign fleets.

So far there has been little direct competition between the United States and foreign fleets in the western Aleutians. Several international agreements restrict the foreign fleets to species and waters not fished by U. S. fishermen, whose catches come mostly from waters inside the 4.8-km (3-mile) territorial limit. Also, the United States has no distant-water trawl fleets, a reflection of the lack of economic incentives to the U. S. fishing industry under institutional and market conditions that have prevailed.

Discussion in this chapter is limited to the current status of commercially exploited fish and whale stocks around Amchitka. Other sections of this volume treat related topics, e.g., physical oceanography (McAlister and Favorite, Chap. 16), marine fish communities (Simenstad et al., Chap. 19), sea mammals (Abegglen, Chap. 20), and sea otters (Estes, Chap. 21).

The area of concern is arbitrarily defined as those waters between longitude 170°E and 170°W and latitude 50°N and 55°N, which coincides with the area designated as Aleutian area 5 by the International North Pacific Fisheries Commission (INPFC) for reporting catch statistics. Amchitka lies in about the center of this area (Figs. 2 and 3). The continental shelf to the east of Amchitka, including the Bering Sea and northeast Pacific Ocean, has very large stocks of fish and intensive fisheries, but they are not considered here.

Only the major species currently sought within the area of concern by U. S. and foreign fishermen are discussed here. These include sockeye salmon (*O. nerka*), chum salmon (*O. keta*), pink salmon (*O. gorbuscha*), coho salmon (*O. kisutch*), chinook salmon (*O. tshawytscha*), Pacific ocean perch, sablefish (*Anoplopoma fimbria*), walleye pollock (*Theragra chalcogramma*), Pacific cod (*Gadus macrocephalus*), Pacific halibut (*Hippoglossus stenolepis*), king crab (*Paralithodes camtschatica*), sperm whale (*Physeter catodon*), sei whale (*Balaenoptera borealis*), and fin whale (*B. physalus*).

Other commercial species in this area, which are not included in the discussion because they make up only a minor portion of the current catch, include tanner crab (*Chionoecetes tanneri*), Dungeness crab (*Cancer magister*), arrowtooth flounder (*Atheresthes stomias*), yellowfin sole (*Limanada aspera*), rock sole (*Lepidopsetta bilineata*), and flathead sole (*Hippoglossoides elassodon*).

There is no single source of statistics for all species caught in the western Aleutians, but I have included catches for the most recent year available (usually 1970 or 1971).

Fig. 2—Japanese fishing areas off Alaska, 1971 (excluding whales).

Fig. 3—Soviet fishing areas off Alaska, 1971 (excluding whales).

DATA SOURCES

Detailed information on the fishery resources in the immediate vicinity of Amchitka Island is scanty. Despite the limitations of available data, it is important to include in this volume a résumé of what we know or can infer about the fishery resources of the western Aleutians because they are potentially the most economically valuable component of the Amchitka marine ecosystem.

The only assessment of local resources was limited sampling of nearshore fish stocks by the University of Washington Fisheries Research Institute (FRI) during the AEC testing program. Although Japanese and Soviet scientists investigated some aspects of the fishery resources in the western Aleutians during their heavy exploitation of demersal fish stocks in the 1960s, most of the results of this research have not been published. In a discussion such as this, the published statistics are adequate to describe the general characteristics of the commercially exploited resources.

The best published sources of catch data are the INPFC, the National Marine Fisheries Service (NMFS), and the information exchanged annually since 1969 between the Soviet Union and the United States at bilateral agreement meetings.

Each year the INPFC publishes a statistical yearbook that tabulates by area and gear the weight of each species caught in the North Pacific Ocean and in the Bering Sea by Japan, the United States, and Canada. The INPFC also publishes the proceedings of annual meetings and bulletins describing research conducted by the three treaty nations on North Pacific fisheries.

The NMFS Division of Enforcement and Surveillance in Alaska publishes an annual summary of observations on patrols of foreign fishing fleets off the Alaska coast. These patrols are made by NMFS enforcement agents in cooperation with the U. S. Coast Guard. Their purpose is to enforce United States fishery laws and regulations, police fisheries subject to international agreements, and maintain surveillance of extra-treaty foreign fisheries. In 1971 the patrols covered about 145,000 km (90,000 miles) by ship and about 380,000 km (236,000 miles) by aircraft.

Several publications describe the general methods of operation of Japanese and Soviet fleets in the Gulf of Alaska and in the Bering Sea and the biology and life history of commercially exploited species, although none of these pertain specifically to the western Aleutian fisheries. The most comprehensive single source of general information is the study by Alverson, Pruter, and Ronholt (1964). These investigators describe the history and methods of fishing for demersal fishes by

foreign and U. S. fishermen and discuss the geographic distribution, relative abundance, and biology of each species. A paper by Reeves (1973) provides similar but more current data for the Gulf of Alaska. Chitwood (1969) provides a concise history of Japanese, Soviet, and South Korean fisheries off Alaska through 1966 and describes fishing vessels, their numbers, and where they fish. Hitz (1970) gives detailed descriptions of vessels and fishing methods used by Soviet trawl fleets. Kasahara (1972) reviews Japanese distant-water fisheries throughout the world; he emphasizes the role of international agreements and predicts that the prospects for continued expansion are not bright. Hart (1973) is one of the most valuable general references for information on distribution and life history of Pacific Coast fishes. My discussions of individual species are drawn principally from these sources.

FISHERY RESOURCES

A caveat that applies to any discussion of abundance of ocean fish stocks is that it is seldom possible to directly and precisely determine the numbers or biomass of any species. Usually commercial fishery catch statistics provide the best basis for estimating relative abundance of a species in a particular area. Catches by Japanese fleets supply these data for the western Aleutians. Soviet catch statistics are not so useful as the Japanese statistics because they are not reported in as much detail and include only recent years. In using catch statistics as a measure of relative abundance, we must assume that the catch reflects actual abundance. This is obviously an imperfect procedure, but it is the best recourse available. It is also important to remember that stocks of species not currently sought by fishermen may be abundant but are not represented in proportion to their numbers in catch records.

The best single source of information for assessing the relative abundance of commercially sought fish in the western Aleutians (excluding salmon, crabs, and whales) is the series of INPFC Statistical Yearbooks, which contain summaries of Japanese catch statistics. In 1969 a new system of reporting catches was initiated. This system identified, for the first time, catches of each species for the western Aleutians specifically (Table 1). Before 1969 catches for the western Aleutians were combined with those from other areas to the east.

Despite the severe reduction of stocks, the catch of Pacific ocean perch is still greater than the catch of all other species combined.

Experimental research trawling by FRI from 1967 to 1972 provides insight into the condition

Table 1—Commercial Catch of Fish (Metric Tons) in the Western Aleutians by Japan and the U.S.S.R., 1969 to 1971

Nation and year	Pacific ocean perch	Sable-fish	Pacific halibut	Arrow-tooth flounder	Yellow-fin sole	Rock sole	Flathead sole	Walleye pollock	Pacific cod	Other
Japan										
1969*	15,597	1,673	330	65	20	2	2	512	222	2,558
1970*	13,650	1,247	351	288	9	2	11	179	284	2,002
1971†	14,664	2,766	387	44	1	1	16	622	432	3,928
U.S.S.R.‡										
1969§	23,172									1,453
1970	53,274							9,490		9,490
1971	7,190	170						2,535	1,653	1,322

*International North Pacific Fisheries Commission (1972a; 1973).

†Fishery Agency of Japan.

‡United States—U.S.S.R. Bilateral Scientific Meetings, 1970, 1971, and 1972.

§U.S.S.R. trawl fishery statistics for 1969, 1970, and 1971. Partial catch (does not include first quarter).

of fish stocks in the immediate vicinity of Amchitka and generally corroborates the relative abundance of species deduced from Japanese catches. The narrative summary by FRI of their catches from 1967 to 1972 (Simenstad et al., Chap. 19, this volume) states that bottom trawl catches ranged between 200 and 1000 fish per hour when dense schools of Pacific ocean perch, Pacific cod, or walleye pollock were encountered and that catch composition typically ranged from 40 to 900 Pacific ocean perch, 30 to 55 walleye pollock, 20 to 45 Pacific cod, 20 to 30 sculpins, 6 to 12 arrowtooth flounder, 6 to 7 rock sole, and 2 to 6 Pacific halibut per trawling hour.

Salmon

Five species of Pacific salmon occur in the western Aleutians as juveniles and maturing adults. They spawn in Asian and North American streams and intermingle in the western Aleutians in varying degrees during the 1 to 4 years they spend at sea.

The best source of information on the relative numbers of the five species in the western Aleutians is the catch records of Japanese fishing fleets. Table 2 shows the mother-ship catches of the Japanese high-seas fleet for each salmon species from 1952 to 1970. Although the effort has remained constant since 1962, the catches fluctuate widely because of annual variations in abundance of each species. The only data on salmon abundance in the immediate vicinity of Amchitka are FRI samples for 1969 and 1970 (International North Pacific Fisheries Commission, 1972b, Tables 8, 9, and 10). Kondo et al. (1965) provide a comprehensive review of ocean distribution and migration of salmon based on tag returns. All three sources indicate that sockeye and chum salmon predominate in most years in the western Aleutians

and that pink salmon are third-most abundant. Coho and chinook salmon are present in insignificant numbers compared with the other three species.

Salmon in the western Aleutians originate from streams in both Asia and North America. Most chum salmon in the western Aleutians are from rivers in the U.S.S.R. and Japan (Shepard, Hartt, and Yonemori, 1968), and most sockeye salmon are from rivers in Bristol Bay, Alaska (Margolis et al., 1966; Bakkala, 1971). The abundance of pink salmon fluctuates greatly. During some years pink salmon of Asian origin predominate; in other years pink salmon from Alaska streams are most abundant (Neave, Ishida, and Murai, 1967). Pink salmon are the predominant species spawning in streams on Amchitka and other Aleutian Islands, but their numbers are relatively insignificant.

There is increasing evidence that many of the chinook salmon caught by the Japanese are from western Alaska rivers, such as the Yukon and Kuskokwim.

Fisheries. Only Japan fishes for salmon in the western Aleutian area. Kasahara (1972) reviews the history and development of this fishery, which began in its present form in 1952 with the signing of the International North Pacific Fisheries Convention by the United States, Canada, and Japan. This treaty requires Japan to abstain from fishing for salmon east of longitude 175°W and was believed to protect from the Japanese fishery most immature salmon originating from North American streams (Fig. 2). Subsequent research has shown that some North American stocks (mainly sockeye, but also some chums, pinks, and chinooks) migrate to the west of this abstention line, and since 1963 the United States and Canada have attempted, without success, to move the line farther west.

Table 2—Japanese Mother-Ship Salmon Fishery Catch* (Thousands of Fish), Longitude 160°E to 175°W

Year	Sockeye	Pink	Chum	Coho	Chinook
1952	738	698	629	24	1
1953	1,534	2,892	2,678	307	3
1954	3,382	2,698	8,254	675	57
1955	9,456	9,108	14,012	1,467	43
1956	8,702	6,589	15,316	3,393	117
1957	19,403	17,204	8,877	193	25
1958	10,708	7,859	14,048	3,106	38
1959	9,125	18,642	12,856	1,388	63
1960	12,879	1,826	10,517	862	180
1961	12,998	3,226	6,128	281	31
1962	10,590	1,011	6,372	1,531	122
1963	8,902	6,242	5,858	1,890	88
1964	7,097	2,198	8,640	3,533	410
1965	12,038	4,238	6,037	1,173	185
1966	7,254	2,457	8,562	466	208
1967	8,087	7,698	6,848	225	127
1968	6,373	3,609	8,107	805	362
1969	5,935	6,862	7,721	1,144	554
1970	6,944	1,573	9,639	180	437

*International North Pacific Fisheries Commission (1972c).

From 1962 through 1971 the Japanese fleet has consisted of 11 factory ships and 369 catcher boats. The salmon are caught in floating monofilament gill nets set off the sterns of the catcher boats (Fig. 4). The nets have a mesh size of about 120 mm stretch measure and are 5 m (16 ft) deep. When all the catcher boats are fishing, more than 5500 km (3400 miles) of net is fished daily because each catcher boat sets 15 linear kilometers of net each day. The catcher boats transfer each day's catch to a factory ship where the salmon are cleaned and frozen whole or canned. The processed catch is transported to Japan where it is marketed locally and throughout the world.

The fishery, which lasts from mid-May until July or August (Chitwood, 1969), starts south of the Aleutian Islands and moves progressively north toward Asia and North America to intercept mature adult salmon migrating toward parent spawning streams. The thousands of net floats and huge wads of derelict gill nets that have accumulated on Amchitka beaches provide striking evidence of this massive fishing effort.

Future Prospects. In 1973 and 1974 the valuable Bristol Bay sockeye salmon run declined to very low levels, apparently as a result of both the Japanese high-seas catch and adverse environmental conditions that caused unusually high mortality of juveniles in the Bristol Bay estuary and lakes. To reverse this decline, the United States has aggressively attempted to persuade Japan to curtail its high-seas fishing and has drastically

curtailed its own catch. The present downward trend of sockeye salmon abundance will probably turn upward if environmental conditions during the fish's early sea life return to normal and international negotiations are successful in restricting catches on the high seas.

Chum and pink salmon seem to be maintaining their numbers better than sockeye. Barring the collapse of international fishery agreements, which limit to some extent the scope of Japanese high-seas fishing, the abundance of pink and chum salmon in the western Aleutians can be expected to continue at more or less the same levels as at present.

If other nations not party to the present fishery agreements between Japan, the United States, and Canada were to begin fishing, the unrestricted fishing could result in the decimation of present stocks of all salmon species.

King Crab

The king crab resource is the most significant present and potential fishery resource for U. S. fishermen in the western Aleutians. The precise size of this resource is undetermined, but it is substantial in localized areas. King crabs are not common at Amchitka. National Marine Fisheries Service biologist—divers saw a few juvenile king crabs during extensive underwater observations at Amchitka over the 5-year period 1969 to 1973, and biologists from FRI captured a few adults

Fig. 4—Japanese catcher boat hauling in salmon gill net. Note salmon on deck and small net astern of the gill net to retrieve salmon that fall out of gill net as it is being hauled aboard. (Photograph courtesy of NMFS Division of Enforcement and Surveillance.)

during the same period. *Lithodes aequispina*, a species similar to king crab, was captured by FRI in research trawls near Amchitka at an average rate of 4 to 9 per hour (Simenstad et al., Chap. 19, this volume).

Biology and Life History. King crabs occur along the entire North Pacific coast from northern Japan to British Columbia, usually on sand or mud bottoms in water depths to 400 m (1300 ft). The commercial fisheries are limited by law and international agreements to males only, which grow larger than females. King crab males may reach a weight of 11 kg (25 lb) and an age of 16 years, although the averages are much less. At Kodiak, Alaska, recent average weights of individual crabs in the catch have been about 3 kg (6 lb) (Haynes and Lehman, 1969). Both sexes mature at about 5 years of age. The fecundity of females ranges from 25,000 to 390,000 eggs (Haynes, 1968). The fertilized eggs are carried externally by the female

for about 11 months and hatch in the spring just before molting and mating again. The larvae are planktonic and may be transported long distances by currents before settling to the bottom (Hebard, 1959; Haynes, 1974). Adults also migrate long distances by walking on the bottom. After they reach maturity, king crabs have few natural enemies.

Fisheries. The U. S. king crab fishery in the western Aleutians is concentrated east of Amchitka around Adak Island, but some exploratory fishing has been done around Kiska and Attu Islands. Significant commercial catches have been made on Petrel Bank, northeast of Semisopochnoi Island.

The Soviets and Japanese are prohibited from fishing for crabs in the western Aleutians under terms of bilateral agreements with the United States.

The U. S. fishermen catch king crabs in baited pots in waters to about 200 m (650 ft) deep. The

pots, which are about 2 m (6 ft) square and 1 m (3 ft) deep, are set on the bottom and attached by line to two buoys at the surface. The pots weigh about 150 kg (300 lb) and are hauled with a power winch. Crab vessels are 15 to 55 m (50 to 180 ft) long [average about 30 m (100 ft)]. The crabs are kept alive in tanks with circulating seawater until they are taken to a shore plant where they are butchered, cooked, and frozen. The U. S. catches west of longitude 172°W for the years 1969 to 1971 were as follows (Alaska Department of Fish and Game, 1972):

Year	Pounds	Kilograms
1969	18,040,000	8,182,800
1970	12,424,800	5,635,800
1971	25,828,100	11,715,400

Fishing is regulated by season and catch-quota restrictions, which vary from year to year.

Future Prospects. Crab fishing by U. S. fishermen on unexploited stocks in the western Aleutians is likely to increase.

Pacific Halibut

Pacific halibut occur on the continental shelf along the entire North Pacific coast from Japan to California in waters to 1100 m (3600 ft) deep (Bell and St.-Pierre, 1970). There is no reliable information on their distribution and abundance in the western Aleutians, but catches by research and commercial vessels indicate that Pacific halibut are present in low abundance throughout the area (Bernard E. Skud, International Pacific Halibut Commission, Seattle, Wash., personal communication). During the recent AEC occupation of Amchitka, sport fishing for Pacific halibut in Constantine Harbor was a popular pastime, and large Pacific halibut were sometimes hooked on baited setlines. The FRI personnel also caught some Pacific halibut near Amchitka with research fishing gear (Simenstad et al., Chap. 19, this volume).

Biology and Life History. Pacific halibut are among the largest fishes in the world. The North American record Pacific halibut [225 kg (495 lb)] was caught at Petersburg, Alaska. The average size of Pacific halibut in the U. S. commercial catch is about 15 kg (33 lb). Females mature later, live longer, and grow faster than males (Bell and St.-Pierre, 1970). Most large Pacific halibut are females. The females reach an age of more than 40 years, and males, about 30 years. The number of eggs produced is proportional to the weight of the

fish, and large females may produce 3 million eggs annually. Pacific halibut migrate long distances; newly hatched young are sometimes carried thousands of kilometers from the spawning locations by currents, and tagged adults have been recovered as far as 3700 km (2300 miles) from the point of tagging (Bell, 1973). Pacific halibut are omnivorous but feed predominantly on other fish and crustaceans, including tanner and king crab.

Fisheries. Pacific halibut along the North American coast are exploited by the United States and Canada. The catch is regulated by the International Pacific Halibut Commission (IPHC). In addition, large numbers of juvenile Pacific halibut are incidentally captured off the Alaska coast by the Japanese and Soviets while trawling for other species. This catch has contributed to the recent declines in North American Pacific halibut stocks. Although Pacific halibut constitute only a small percentage of the total trawl catch, in aggregate, these trawl-caught Pacific halibut amount to a significant portion of the Pacific halibut resource in the Bering Sea. The IPHC has reduced the catch limits of the North American setline fishery, but the expected benefits have been negated by the growing incidental catch.

In the United States and Canadian fisheries, Pacific halibut are caught with baited hooks fastened to 1.5-m (5-ft) lengths of light line (gangions) attached at regular intervals to a heavy groundline (skate) lying on the sea bottom. Each skate (a unit of gear) is about 550 m (1800 ft) long and is anchored and marked by surface buoys at each end. The gear is pulled with a power winch after fishing for periods of a few hours to more than a day. The fish are cleaned immediately and transported to shore plants where they are frozen.

Pacific halibut from the western Aleutians constitute only a small part of the total United States-Canadian landings. The fishing intensity in this area varies greatly from year to year because of its distance from processing plants. The area is therefore attractive to fishermen only when areas to the east are closed to fishing. During recent years the catch in the western Aleutians ranged from 1 to 69 metric tons (Bernard E. Skud, International Pacific Halibut Commission, Seattle, WA., personal communication):

Year	Canada, metric tons	U. S., metric tons	Total, metric tons
1969	3	56	59
1970	38	31	69
1971	0	1	1
1972	9	16	25

Future Prospects. Because of the limited size of the stocks and the distance from processing plants, it is unlikely that Pacific halibut fishing in the western Aleutians will expand much beyond its present relatively low level.

Pacific Ocean Perch

Pacific ocean perch have been (and may still be) the most abundant fishery resource in the western Aleutians, but intensive fishing by fleets of Soviet and Japanese trawlers during the 1960s caused a precipitous decline in abundance. Chitwood (1969) summarizes the development of these fisheries.

Biology and Life History. Pacific ocean perch adults occur in dense schools throughout Alaska's continental shelf south of the Bering Strait at depths of 150 m (490 ft) to over 400 m (1300 ft), generally over rocky bottoms (Major and Shippen, 1970). During the first few weeks of life, the larvae are planktonic and drift with the currents. Since no verified collections of perch between the larval stage and year-old juveniles have ever been reported (Carlson and Haight, in press), the balance of their first year is unknown. Juveniles over the age of one year live in relatively shallow water [55 to 130 m (180 to 425 ft) deep]. In the fifth or sixth year of life, they mature and join adult offshore stocks in deeper water. They are long lived and slow growing, reaching a maximum age of about 30 years and a maximum size of about 45 cm (17.5 in.) and 2 kg (4.5 lb) (Alverson and Westrheim, 1961).

Juvenile Pacific ocean perch (1 to 5 years old) feed mainly on copepods and euphausiids. Young juveniles (1 to 2 years old) prefer copepods, and older juveniles (3 to 5 years old) prefer euphausiids (Carlson and Haight, in press).

Adults also feed on copepods and euphausiids but show a preference for euphausiids. Other larger food items, e.g., shrimp and squid, make up a significant part of their diet (Shalkin, 1964; Paraketsov, 1963; Lyubimova, 1965).

Fisheries. Pacific ocean perch in the western Aleutians are fished exclusively by the Soviets and Japanese. The history of the fishery encompasses a period of only a few years, i.e., from the first explorations of Pacific ocean perch stocks in the late 1950s by Soviet research vessels to one of the most massive fishing operations in history in the 1960s and to the present reduced level of effort. During that brief period the large virgin stocks of Pacific ocean perch in the Bering Sea and Gulf of Alaska were greatly reduced, and by 1968 only 39% of the original stock biomass remained (Quast, 1972). Quast's estimate was for the total North

American Pacific ocean perch resource, but it is reasonable to assume that western Aleutian stocks of Pacific ocean perch have followed the overall pattern of decline. Published data are not available for catches of perch by Japan and the Soviet Union for specific areas over a series of years. The most useful data illustrating the rise and decline of Pacific ocean perch catches are Japanese statistics for the Bering Sea region, which includes the western Aleutians (International North Pacific Fisheries Commission, 1973, Table 32):

Year	Catch, metric tons	Year	Catch, metric tons
1961	13,002	1966	50,308
1962	12,449	1967	38,517
1963	17,257	1968	54,347
1964	43,750	1969	30,892
1965	47,648	1970	22,772

The Japanese and Soviets use the same fishing methods for Pacific ocean perch and other demersal fish. Schools of fish are first located by electronic hydroacoustic instruments, and then trawl nets are dragged through the water to intercept the schools. These schools contain predominantly Pacific ocean perch, but small numbers of other species are also caught. The catch is hauled aboard ship either over the side or over the stern (Fig. 5) and cleaned immediately (Fig. 6). Most are processed into frozen fillets. Nearly all fishing is now by large stern-ramp factory trawlers of 50 m (160 ft) to more than 100 m (320 ft) long (Figs. 7 and 8). These trawlers are completely self-sufficient, i.e., they are equipped to catch, process, and store the finished product until it is transferred to a refrigerated transport ship (Fig. 9) or until they return to the parent country. In the 1960s smaller trawlers were common, but the trend is toward larger ships.

Both Japan and the Soviet Union generally fish in summer (May–November) when Pacific ocean perch are more vulnerable to capture by trawling; in winter the perch are in deeper water (Gunderson, 1974). In 1971 between 1 and 6 Soviet trawlers and 2 and 10 Japanese trawlers operated in the western Aleutians (National Marine Fisheries Service, 1973).

Future Prospects. Because of the depleted condition of the stocks and because Pacific ocean perch grow very slowly, the present relatively low level of fishing effort will probably continue.

Sablefish

Sablefish are distributed throughout the North Pacific Ocean from California to Japan. In the

Fig. 5—Catch of 20 metric tons (44,000 lb) of ocean perch being hauled in over the stern ramp of a Japanese trawler. (Photograph courtesy of Jiro Nishimoto, National Marine Fisheries Service.)

Fig. 6— Japanese fisherman cleaning ocean perch aboard stern-ramp trawler. (Photograph courtesy of Jiro Nishimoto, National Marine Fisheries Service.)

Fig. 7—Japanese stern-ramp trawler *Taiyo Maru* No. 81 at dock in Shimonoseki, Japan, before leaving on fishing voyage to Alaska waters. (Photograph courtesy of Jiro Nishimoto, National Marine Fisheries Service.)

Japanese catch in the western Aleutians, sablefish are second in abundance to Pacific ocean perch. They do not comprise as great a proportion of the total Soviet catch, presumably because the Soviets do not use longline gear (the most effective sablefish gear).^{*} Sablefish were not common in catches by FRI in the immediate vicinity of Amchitka Island (Simenstad et al., Chap. 19, Table 3, this volume), but Kobayashi (1957) caught larval sablefish in the western Aleutians in July and August of 1955 and 1956.

Biology and Life History. Sablefish are known by the common name black cod in Alaska, but they are not taxonomically related to the true cods and bear only a superficial resemblance to them.

The following summary of what is known of sablefish distribution and biology is derived from Reeves (1973). Adult sablefish prefer deep water and are caught to depths of 530 fathoms (3200 ft); juveniles often occur in shallower waters (even intertidally). They reach maturity between 6 and 8

years of age and at 9 years are about 100 cm (39 in.) long and weigh about 18 kg (40 lb). Spawning takes place in deep water during the late winter, and the eggs and larvae are planktonic. Small immature fish frequent shallow bays and inlets during the late spring and early summer, often in the surface waters. Food items consist of Pacific herring (*Clupea harengus*), Pacific sand lance (*Ammodytes hexapterus*), and crustaceans. Tagging has shown that sablefish migrate long distances, e.g., from Alaskan waters to the Asian coast and from Puget Sound, Wash., to the Bering Sea. Sablefish apparently spawn in the western Aleutians because Kobayashi (1957) captured larval sablefish at nine locations in this area.

Fisheries. Sablefish are caught by Soviet and Japanese trawlers in the western Aleutians with the same gear and in the same areas as Pacific ocean perch. The Japanese also have a longline fishery specifically for sablefish. The longline gear is similar to that used by the U. S. and Canadian halibut fisheries (see the section on halibut). From 1969 to 1971, between 20 and 50% of the Japanese catch of sablefish in the western Aleutians was by longline.

^{*}U. S.—U.S.S.R. Bilateral Scientific Meeting, 1972; U.S.S.R. trawl fishery statistics for 1971.

Fig. 8—Stern-ramp trawler *Taiyo Maru No. 81*. Complex superstructure and rigging is used to set and haul the trawl net and manipulate the gear after it comes aboard. (Photograph courtesy of Jiro Nishimoto, National Marine Fisheries Service.)

Fig. 9—Soviet refrigerated transport anchored in Aleutian waters while transferring fish products from stern-ramp trawlers. The transport is about 130 m (430 ft) long, and the two trawlers are about 85 m (280 ft) long. (Photograph courtesy of NMFS Division of Enforcement and Surveillance.)

Sablefish are a highly esteemed food fish in Japan. They are usually marketed filleted and frozen, but their fine texture and high oil content also make them a superior salted or smoked product.

Future Prospects. The catch of sablefish in the western Aleutians will probably continue at about the same level. Most will continue to be caught incidentally by fishermen trawling for other species, such as Pacific ocean perch.

Walleye Pollock

Walleye pollock (also known as Alaska pollock and Pacific pollock) were, until recently, the only remaining large unexploited stocks of fish off the North American continental shelf (Kasahara, 1961). The Japanese catch of pollock in the eastern Bering Sea region increased from 24,000 metric tons in 1961 to more than 1,200,000 metric tons in 1970 (International North Pacific Fisheries Commission, 1973, Table 32). Pollock are apparently abundant around Amchitka (Simenstad et al., Chap. 19, Table 3, this volume). Soviet and Japanese trawlers are switching to pollock as a

prime target species (Kasahara, 1972; National Marine Fisheries Service, 1973), although Pacific ocean perch still predominate in western Aleutian trawl catches (Table 1). This recent shift of emphasis to pollock is primarily a consequence of depletion of other species and of new developments in food technology, which have generated a heavy demand for minced pollock to use in making surimi, a fish paste that is blended with other food products (Miyauchi, Kudo, and Patushnik, 1973). Previously the demand for pollock as human food was slight in both the Soviet Union and Japan.

Biology and Life History. Temperature apparently determines where pollock occur (Kasahara, 1961). They are caught at all depths where the water temperature is between 0 and 10°C. Pollock mature when 3 or 4 years old and form dense schools during spawning migrations in winter and spring. The eggs are planktonic, and the young hatch in about 12 days. Pollock commonly reach an age of 8 years, but some reach an age of 15 years and a weight of 18 kg (40 lb). The primary foods are planktonic crustaceans, mostly euphausiids, although shrimp and fish are also

important. The diet varies in different geographic areas and is probably determined by the availability of food.

Fisheries. Walleye pollock are caught mostly by large stern-ramp Japanese and Soviet trawlers with the same type of gear as is used for Pacific ocean perch. In 1971 Japanese trawlers caught 622 metric tons of pollock in the western Aleutians, and Soviet trawlers caught 2535 metric tons in the same area (Table 1).

Future Prospects. Future prospects are uncertain. Although the pollock catch and demand are increasing, there is evidence in the eastern Bering Sea, where the largest catches off Alaska are made, that catch per unit of fishing effort is dropping and the bulk of the catch increasingly comprises young and immature fish (Pruter, 1973). The Bering Sea situation may be different from that of the western Aleutians, however, and there appear to be substantial stocks of pollock that have only begun to be exploited. Therefore it is likely that catches near Amchitka will increase.

Pacific Cod

One of the earliest commercial fisheries in Alaska was for Pacific cod. Stocks in the Aleutian Islands and Bering Sea were first exploited commercially in 1864, and their great abundance was first noted and recorded by a Russian navigator in 1765 (Cobb, 1916; 1927). The catch by U. S. fishermen reached its maximum in the early part of the twentieth century; in most years between 1905 and 1925, the average catches were between 2.5 and 3.9 million fish (Kasahara, 1961). Pacific cod fishing by U. S. fishermen has been at a low level off Alaska for many years because of the lack of U. S. market demands. Pacific cod are still widely distributed and abundant on Alaska's continental shelf, and the present stocks are virtually unexploited. They are apparently abundant around Amchitka in offshore waters (Isakson, Simenstad, and Burgner, 1971). Several dead Pacific cod were found washed ashore on Amchitka after the Cannikin explosion.

Biology and Life History. Pacific cod live near the bottom at depths to 400 m (1300 ft) around the entire North Pacific rim from California to Honshu, Japan (Kasahara, 1961). They apparently migrate to shallow inshore areas in summer and to deeper offshore areas in winter; these movements are related to temperature. Females have between 1.4 and 6.4 million eggs; they may reach a maximum weight of about 18 kg (40 lb) after 15 years of growth, although size, age, and fecundity vary widely. They feed on a variety of invertebrates and fish.

Fisheries. Pacific cod in the western Aleutians are caught incidentally by Soviet and Japanese trawl fleets and by Japanese longliners fishing for sablefish. Soviet catches are greater than Japanese catches; e.g., in 1971 the Soviets caught an estimated 1653 metric tons of Pacific cod in the western Aleutians whereas the Japanese landed only 432 metric tons. Pacific cod are filleted and frozen and are considered a delicacy.

Future Prospects. The catch of Pacific cod in the western Aleutians is likely to increase as other target species decline in abundance because the large stocks are still only lightly exploited.

Whales

Many aspects of the biology and distribution of whales are poorly known despite more than 100 years of worldwide exploitation. There is consequently little information about whale stocks around Amchitka. Between 1968 and 1973 whales were occasionally sighted from shore by personnel at Amchitka, but their species was not verified. Several dead sperm whales washed ashore on Amchitka during the AEC occupation.

Mackintosh (1965) and Slijper (1962) are two of the best sources of general information on whales and the whaling industry. Nishiwaki (1966) describes the distribution and migration of whales in the North Pacific Ocean on the basis of the kill by the Japanese whaling industry between 1945 and 1962. In the Rat Islands area (which includes Amchitka), more sperm whales (*Physeter catodon*) were taken than any other species, but blue whales (*Balaenoptera musculus*), humpback whales (*Megaptera novaeangliae*), fin whales (*Balaenoptera physalus*), and sei whales (*Balaenoptera borealis*) were also taken. Presumably these five species are still present, although the killing of blue and humpback whales is now prohibited, and their occurrence is no longer reflected in whaling statistics.

Biology and Life History. Only the three species of whales still hunted and occurring in the Aleutians (sperm, fin, and sei) are discussed.

The sperm whale is a toothed whale that reaches a length of 18 m (60 ft). Sperm whales are polygamous, and the males are much larger than the females. Their distribution is worldwide except for polar regions. Several species of squid are their primary food.

In the northern hemisphere the fin whale, a baleen whale, reaches a length of 24 m and is second in size only to the nearly extinct blue whale. Fin whales are monogamous, as are all baleen whales. Their distribution is worldwide; in

Alaska waters their distribution extends into the Arctic Ocean in summer. They are filter feeders, straining planktonic crustaceans and small fishes from the water by horny bristled plates (baleen) that are attached to the roof of the mouth. A large fin whale may have as many as 400 of these plates spaced about half an inch apart on each side of the upper jaw (Mackintosh, 1965).

Sei whales are relatively small baleen whales that reach a maximum length of 15 m (50 ft). Because of their low oil content, they were not harvested to any extent until recent years when stocks of the larger species of whales were reduced to the extent that hunting them became uneconomical. They are widely distributed in subarctic waters throughout the world and are common in Aleutian waters (Nishiwaki, 1966).

Fisheries. Japan and the U.S.S.R. are the only nations that now hunt whales commercially in the Gulf of Alaska and in the Bering Sea. A severe worldwide decline in numbers of whales as a result of excessive killing and consequent restriction of the kill by the International Whaling Commission are responsible for the present limited extent of the whaling industry. In 1971 the Japanese had 3 North Pacific Ocean fleets with 26 killer vessels; the Soviets operated 2 factory ships and 28 killer vessels (National Marine Fisheries Service, 1973). Table 3 shows the Japanese and Soviet pelagic whale kill for 1969 to 1971 in all North Pacific Ocean waters. Sperm whales make up the majority

Table 3—Japanese and Soviet North Pacific Ocean Whale Kill, 1969 to 1971*

Nation and year	Sperm	Sei	Fin
Japan			
1969	3000	3591	576
1970	2700	3235	518
1971	1803	2431	542
U.S.S.R.			
1969	8211	1091	593
1970	8585	782	412
1971	5525	296	190

*From National Marine Fisheries Service (1973).

of the kill (Nishiwaki, 1966). The whaling season occurs from May to October, and hunting takes place far offshore. In 1971 no whales are believed to have been taken near Alaska by the Soviets, and only 622 whales, or 13%, of the Japanese kill was from Alaska waters (National Marine Fisheries Service, 1973).

After the whale is hauled aboard the factory ship, the entire whale is converted to food or

industrial products. Sperm whale oil is used only for industrial oils, whereas much of the oil of baleen whales is used for edible products, especially margarine. The meat of all species is used for human and pet food; that of baleen whales is similar to beef in palatability.

Future Prospects. The numbers of whales taken each year will probably continue to decline because of restrictive regulations to prevent further reduction of the stocks. Further, world opinion is mobilizing against harvest of any whales. For these reasons the high-seas whaling industry will probably come to an end within a few years.

[Author's Comments]

Since the foregoing was prepared, the outlook for future foreign exploitation of fishery resources in the western Aleutians has been complicated by the probability of unilateral action by the United States extending its fishery jurisdiction from 12 miles to 200 miles offshore. Legislation has passed both houses of Congress, and the President is expected to sign the ultimate bill, which is likely to become effective by mid-1977.

Except for salmon and whales, most of the other currently exploited fishery stocks of the western Aleutians are within 200 miles of land. What action will be taken with regard to these fishery resources and what the effect of this action will be is difficult to predict.

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Oceanography

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Circulation near Amchitka Island is influenced by complex patterns of exchange and mixing between the North Pacific Ocean and Bering Sea waters in the passes of the Aleutian Islands, resulting in wide variations in physical, chemical, and biological conditions seasonally, and also over short geographic distances. Strong westward flow in the Alaskan Stream south of Amchitka Island brings water of 2 to 4°C into the area in winter, ameliorating sea and air temperatures and inhibiting the development of extensive shore ice.

During spring and summer, coastal turbulence reduces thermal stratification in the surface layer, and inshore water temperatures are 1 to 4°C lower than in the offshore oceanic regimes. Zooplankton are typical subarctic Pacific forms. Zooplankton volumes in the 0- to 150-m surface layer increased roughly one order of magnitude from winter to summer. Nutrients do not appear to be limiting for phytoplankton growth.

The bulk of oceanographic research has taken place in those areas of the ocean which present the most enticing lure to man. This attraction most often takes the form of a bountiful fishing ground or an economical practical sea route. Research data on the large circulations of water in and between the Bering Sea and the North Pacific Ocean have accumulated mainly in conjunction with the expansion of the area's fisheries and are only now beginning to include detailed information on circulation in the passes of the Aleutian Islands and in the nearshore waters of the individual islands.

The Aleutian-Commander Island arc divides the Bering Sea from the North Pacific Ocean along a stretch of 1500 km. The arc is submerged in 39 places, forming passes and straits, but only 14 of these have an area greater than 1 km² or a sill depth deeper than 200 m. The series of passes among the Aleutian Islands is unique; the shallow sills connecting many of the islands block the free exchange of intermediate and deep water between the Bering Sea and the North Pacific Ocean. The deepest pass in the Aleutian portion of the island arc is Amchitka Pass, which has a sill depth greater than 1000 m. Because of exchange through this pass, the oceanography of the Amchitka Island area is related to offshore areas in both the North Pacific Ocean to the south and the Bering Sea to the north.

PHYSICAL OCEANOGRAPHY

Subarctic Pacific Circulation

The subarctic Pacific region of the North Pacific Ocean is defined as bounded on the north by Bering Strait, the land constriction at the entrance to the Arctic Ocean, and on the south at about 40°N by a change in vertical water structure. The southern edge, where marked temperature inversions that are characteristic of surface dilution and winter cooling end and marked salinity inversions that are characteristic of net surface evaporation begin, is generally referred to as the subarctic-subtropical boundary and for convenience is specifically denoted by the 34 ‰ isohaline in the surface layer (Fig. 1). The predominant oceanic feature of the region is the large cyclonic subarctic gyre. Formed by a merging of currents off Japan and driven by local winds, water in the gyre moves eastward across the North Pacific Ocean and sweeps around the Gulf of Alaska and northward into and around the Bering Sea. Oceanographic conditions in this region were extensively reviewed by Favorite, Dodimead, and Nasu (1976). Only a summary is presented here.

Southward flow (Oyashio) along the northeastern coast of Japan and northward flow (Kuroshio) along the southeastern coast of Japan converge, mix, and turn eastward across the North

Fig. 1—Subarctic Pacific region showing basic subarctic gyre and associated currents: 1, Oyashio; 2, Kuroshio; 3, subarctic; 4, Alaskan Stream; 5, Aleutian; 6, Amukta; 7, Amchitka; 8, Buldir; 9, West subarctic; 10, Near; 11, Commander; 12, Transverse; and 13, East Kamchatka.

Pacific Ocean, forming a transition zone between the cold dilute subarctic waters and the warm saline subtropic waters. Although the demarcation of these two flows is sharp and abrupt in the western part of the ocean, it becomes gradually more diffuse as stirring, advection, and diffusion occur during the transpacific travel and characteristic broad, weak, boundary currents occur at the eastern side. Net inflow at the western side of the ocean from the confluence of the Kuroshio and Oyashio as well as other factors, such as deep flow, precipitation, and river runoff, is balanced by a net discharge southward at the eastern side of the ocean in the area of the divergence of the Subarctic Current. The northward flow at the eastern side into the Gulf of Alaska is largely constrained by the Alaskan coast to turn southwestward out along the Alaska Peninsula as the Alaskan Stream. Exchanges with the Bering Sea occur at the northern edge of the Alaskan Stream (Favorite, 1967) at the various openings in the Aleutian-Commander Island arc from 165°W to 170°E. These exchanges occur to various levels, depending on sill depths of the passes, which generally increase in depth to the west. Of the approximately 40 passes, those of major significance to flow are Unimak, 165 to 177°W, 60-m depth (although shallow, this is the first major opening into the Bering Sea); Amukta, 170 to 172°W, 430 m; Amchitka, 178°W to 179°E, 1155 m; Buldir, 176 to 174°E, 640 m; Near, 172 to 169°E, 2000 m; and Kamchatka, 163 to 155°E, 4420 m. The major component of surface flow sweeps westward along the south coast of Amchitka Island and turns northward into the Bering Sea through Near Strait, east of the Commander Ridge. This flow impinges on the Near Current in the vicinity of 170°E and turns northward into the Bering Sea; westward flow, below the sill depth of Near Strait (2000 m), continues along the south side of the Aleutian-Commander Island arc to 166°E, merging with but underriding westward flow in the West Subarctic Current, and then turns northward into the Bering Sea through Kamchatka Strait. North of Near Strait the northward flow merges with the eastward flow, the Commander Current, along the north side of the island arc, and the combined flow subsequently diverges, sending one branch northward along the west side of the Olyutorskiy Ridge and the other eastward around Bowers Ridge into the southeastern part of the central basin where it is joined by the Amchitka and Amukta branches of the Alaskan Stream. A frontal zone occurring at the western edge of the continental shelf in the eastern Bering Sea indicates that the main flow, the Transverse Current, turns northward following the

continental slope and then southwestward along the Siberian coast. At Cape Olyutorskiy a southward branch forms an eddy in the northern Bering Sea, but the main flow continues southwestward and completes the overall cyclonic circulation in the Bering Sea. The East Kamchatka Current continues southwestward along the coast, completing the circulation around the subarctic gyre.

At least 3 to 4 years would be required for a hypothetical surface-water parcel to pass around the periphery of this gyre. Drift-bottle studies (Favorite and Fisk, 1971) indicate that about 2 years are required to traverse the southern boundary, several months to circuit the Gulf of Alaska, less than a year to exit the Bering Sea, and several months to move southward along the Kuril Islands. During this traverse the parcel (and thus any planktonic biota associated with it, assuming confinement in the surface layer and neglecting vertical movements associated with diel and seasonal vertical migrations) would be exposed to a wide range of environmental conditions, e.g., maximum temperatures of 20°C occurring off Japan and minimum temperatures of -2°C in the northern Bering Sea. Numerous subsidiary gyres and eddies can, of course, cause considerable departures from the overall basic cyclonic flow.

Flow in the Aleutian Area

Several methods for the measurement of flow and currents are available. The most direct but most difficult is direct observation. Not only are the problems of positioning and measurement formidable but also net currents tend to be small; thus the net currents may be masked by large turbulent velocities, which make point estimates of currents ambiguous. Other methods are to infer currents and flow from drift-bottle observations, distributions of properties, observed density fields (geostrophic currents), and requirements of continuity of flow. All these methods have been used to some extent to describe the flow through the passes of the Aleutian Islands.

Favorite (1974) used a convenient grouping for the passes, dividing them into east, central, and west pass groups and Commander-Near and Kamchatka Straits (Fig. 2); 99.9% of the area of the openings through the island arc is contained in these five major pass groups (Table 1). Amchitka Pass, in the central Aleutian group, is the only pass east of 172°E that exceeds 1000 m in depth, and only in Kamchatka Strait do depths exceed 2000 m. The major currents through these openings, as indicated in the previous section, are the Amukta, Amchitka, Buldir, Near, and Commander Currents; the source of these flows is largely the

Fig. 2—Vertical profile of all openings through the Aleutian-Commander Island arc and selective groupings of major ones.

Table 1—Depth and Area of the Major Openings in the Aleutian-Commander Island Arc

General opening	Pass/Strait	Depth, m	Area, km ²
East Aleutian group	Unimak	60	0.9
	Samalga	200	3.9
	Chuginadak	210	1.0
	Herbert	275	4.8
	Yunaska	457	6.6
	Amukta	430	19.3
	Seguam	165	2.1
Central Aleutian group			38.6
	Tanaga	235	3.6
	Amchitka	1155	45.7
West Aleutian group			49.3
	Kiska	110	6.8
	Buldir	640	28.0
Commander-Near Strait			1.7
	Near	2000	36.5
	Commander	105	239.0
Kamchatka Strait			3.5
		4420	242.5
Total area			335.2
			702.2

Alaskan Stream. This boundary current has speeds of 50 to 100 cm/sec, and, although distributions of water properties around the head of the Gulf of Alaska at times may indicate some lack of continuity in flow in the surface layer, continuity always exists below 300 m. Normally the Coriolis forces on the westward flow in the Alaskan Stream would result in an elevation of the sea surface shoreward and a tendency for the water to not only hug the coastline but also to veer to the right

(northward) through any openings in the island arc; however, this is not always the case. An appreciable component of flow in the upper 200 to 300 m is southward (the Aleutian Current), closing circulation in the surface layer of the Alaskan gyre. At times inshore countercurrents with speeds in excess of 10 cm/sec occur along the continental slope, but the continuity of such flows is poorly documented—these eastward flows may be associated with large eddies in the Alaskan Stream.

Thomson (1972) described conditions that may cause instabilities and separation of the flow from the coast.

Although the dominant flow in the passes is tidal, there is increasing evidence that eddies exist which encompass major island clusters and require both north and south flows through the passes. Records of direct-current measurements in the Aleutian passes by the U. S. Coast and Geodetic Survey commenced in 1934 with data collected near Unimak Pass, and these data are of considerable value in describing maximum tidal velocities. However, estimates of nontidal components of these measurements are of questionable value because of the limited time scale used in the measurements. Of the 18 records, 5 were of only 1-day duration; 13 other measurements taken from 1934 to 1946 covered periods of 2 to 8 days.

Reed (1971) analyzed 25 surface tidal-flow records from radio current meters suspended from buoys anchored in various passes for intervals of over 4 days during 1949 to 1956. Northerly and southerly net flows were recorded at some locations although at different times. Problems are encountered in such observations when the movement of the vessel or buoy may be greater than the flow. This was clearly demonstrated by observations recorded aboard the U. S. Coast and Geodetic Survey vessel *Surveyor* in Amchitka Pass ($51^{\circ}35'N$, 180°) in the late spring of 1963 when precise positioning at 15-min intervals indicated vessel speed as great as 85 cm/sec at anchor. The direct-current observations from the Amchitka area are considered in detail in a later section.

Eight drift-bottle experiments were made between 1957 and 1972 in the Aleutian area (Favorite, 1974). Releases of bottles well south of the Aleutian Islands from a merchant ship of opportunity in the fall of 1964 implied a northerly drift from five of seven release locations southward of Adak Island, several recoveries being made on Attu Island (the affinity of Attu Island for drift bottles released from all directions was also reflected in recoveries of bottles released from the research vessel *George B. Kelez* during an oceanographic cruise in the winter of 1966). One bottle released south of Amchitka Island in 1964 was recovered on the Pribilof Islands. Two bottles released north of Amchitka Pass in 1971 were recovered on the Pribilof Islands (Favorite and Ingraham, 1972), but bottles released to the north and south of this location were recovered on Amchitka Island (Favorite and Ingraham, 1973). In general, drift-bottle recoveries have reflected flow implied by the distribution of water properties.

A number of authors have examined the density and wind-stress fields in the Aleutian area

in an attempt to ascertain the water exchange between the North Pacific Ocean and the Bering Sea. Arsen'ev (1967) summarized oceanographic conditions in the Bering Sea in an exhaustive analysis of station data prior to 1959. He considered the Commander-Near Strait as the most significant source of flow into the Bering Sea (4.4 Sv),* whereas only 0.7 Sv occurred through the western groups; no net exchange was considered to occur in the eastern Aleutian passes. These transports appear derived from a reference depth of 3000 db, and it is also apparent that, except for a deep inflow in Kamchatka Strait, almost the entire flow into the Bering Sea was derived from the Alaskan Stream (Table 2). On the basis of continuity of the Alaskan Stream, Favorite (1974)

Table 2—Flow (Sv) Through Aleutian—Commander Island Arc

Pass	Transport out of Bering Sea	Transport into Bering Sea	
	Arsen'ev	Arsen'ev	Favorite
Kamchatka	18.4		
Commander—Near		14.4	10.0
Western Aleutian group		0.7	0
Central Aleutian group		4.4	4.0
Total	18.4*	19.5	14.0

*1.1 Sv loss through Bering Strait.

summarized flow into the Bering Sea. Mean annual transport of 12.5 Sv in the Alaskan Stream south of Adak Island was obtained with 4000 db (about 4000 m) as a reference level. Because only Kamchatka Strait is deeper than 2000 m, 1.5 Sv of this flow reaches this westernmost passage. Favorite found no net exchange in the western or eastern Aleutian passes. Of the 11 Sv above 2000 db, 4 Sv is lost through the central Aleutian passes, 3 Sv is gained across the southern boundary, and 10 Sv flows northward through the Commander-Near Strait west of Attu Island. The result is a net annual flow of 14 Sv into the Bering Sea. This result falls between the transport values of 8.0 Sv proposed by Batalin (1964) and 19.5 Sv proposed by Arsen'ev (1967).

WINTER DATA 1968

Observations of temperature, salinity, and selected chemical properties were conducted in

*Sv = Sverdrup = $1 \times 10^6 \text{ m}^3/\text{sec}$.

January–March 1968 in support of the AEC Supplemental Test Site Program on Amchitka Island (Fig. 3). These data permit a description of the marine environment in the vicinity of Amchitka Island.

A brief drogue and dye current study was conducted in February 1968 (McAlister et al., 1968). One 10-m parachute drogue was set in the channel north of Amchitka Island and followed for 5 hr, during which time it moved counterclockwise at 25 to 40 cm/sec. Additional drogue studies were undertaken south of Adak Island in the summer of 1969 (Favorite, Ingraham, and Fisk, 1972). These studies again indicated the strong tidal component of current in this area and the great difficulty of attempting to derive meaningful net current values from a limited program of direct current measurements.

Temperature

Surface temperatures in the North Pacific Ocean are normally lowest during March when winter convective overturn forms an isothermal layer that may extend from the surface to 100 m.

The coldest surface temperature (2.7°C) was observed in the western portion of the study area. The warmest water (3.4 to 3.7°C) was also relatively low in salinity and characteristic of water transported westward by the Alaskan Stream. Water in the island passes, intermediate in temperature (3.0 to 3.2°C), represents a mixture of the warm Alaskan Stream water with cooler water from the Bering Sea. Near the shore Alaskan Stream water occurred as a core of warm water with a maximum temperature of 3.8°C between 150 and 400 m (see Fig. 6). Although inversions and layering were frequent, continuity of the core structure through Amchitka Pass indicated a net northward flow of Alaskan Stream water. Below about 500 m the temperatures decreased gradually with depth, and the vertical distribution of temperature was similar in structure to salinity.

Salinity

Considerable freshwater runoff enters the coastal area of the Gulf of Alaska and is advected westward south of the Aleutian Islands by the Alaskan Stream into the western North Pacific

Fig. 3—Locations of oceanographic stations during Amchitka study, January–March 1968 (Research Vessel *George B. Kelez*).

Fig. 4—Temperature distribution on sigma-t surface = 26.5 (100- and 1000-fathom isobaths shown).

Ocean. Sharp fronts and eddies form at the confluence of the Gulf of Alaska water and the more saline Bering Sea water that is usually present at the Aleutian Passes west of Unimak Island. This feature is present even during winter when runoff to the Gulf of Alaska is diminished by freezing and when seasonal overturn causes mixing of surface water with more saline water to depths of about 100 m. At the axis of the westward flow is a tongue of dilute water ($<32.8\text{‰}$). Bering Sea water (characteristically $>33.0\text{‰}$) was not found south of the entrance to Amchitka Pass. Offshore, North Pacific water had a slightly higher salinity ($\sim 32.9\text{‰}$) than Alaskan Stream water.

Salinity increased with depth; the most rapid change occurred in the well-developed halocline between 100 and 300 m. South of the island arc, characteristic ridging of salinity and temperature was seen at all sections. The sharpest halocline was well offshore at about $50^{\circ}30'N$. Although surface dilution in the Alaskan Stream would be expected to enhance a strong coastal halocline, the halocline was less developed toward shore and weakest in the turbulent passes where high-salinity water of the Bering Sea was mixed in the surface layer.

Density

The distribution of density, calculated from the observed temperature and salinity, was domi-

nated by and generally similar to the distribution of salinity. The greatest stability occurred well offshore with intermediate stability in the Alaskan Stream and the weak to neutral stability in the Aleutian passes.

Water masses mix most easily along sigma-t (equal-density) surfaces. The distribution of temperature on a sigma-t surface indicates the extent of horizontal mixing and suggests movement of water masses at various depths. South of Adak Island the temperature distributions on the sigma-t = 26.5 surfaces showed tongue-like extensions westward toward Amchitka Island (Fig. 4). These extensions represented a westward advection at depth of relatively warm water by the Alaskan Stream from its source in the Gulf of Alaska. At shallow depths, which are influenced by seasonal overturn (0 to 100 m), the coldest water was south of Amchitka Island near $51^{\circ}N$, and water of intermediate temperature occurred north of Amchitka Pass in the Bering Sea. At depths greater than 150 m (sigma-t = 26.0 to 26.5), the coldest water was in the Bering Sea, and water of intermediate temperature occurred south of Amchitka Island. This reversal of temperature gradient with depth suggests that the warmer water of the Gulf of Alaska and the Alaskan Stream had mixed northward into the Bering Sea; at shallow depth, below sill depths, however, horizontal mixing is restricted by the barrier at the island arc.

Fig. 5—Geopotential topography (dynamic meters referred to 1500 decibars) indicating surface flow.

Flow

Except for north-south tidal excursions through the shallow openings in the island arc (and probable shelf waves), westward flow south of the Andreanof Islands follows the general zonal trend of isobaths from 172°W to Amchitka Pass where an irregular bathymetry is encountered. Considerable mixing results which is due not only to flow funneling through channels between the islands lining the eastern side of the pass but also to the impingement of eastward and southward flow from the Bering Sea at the western side of the pass. Roughly 20 to 30% of the flow in the Alaskan Stream moves northward through Amchitka Pass, and Amchitka Island appears to be near the critical focal point where this divergence occurs (Fig. 5). East of Amchitka Island an eastward counter-current occurred seaward of the edge of the continental shelf.

Flow through Amchitka Pass is extremely complex at all depths. North-south vertical sections through Amchitka Pass indicated a northerly current on the east side of the pass and one flowing to the south on the west side at a depth as determined from the distribution of properties (Fig. 6). Relative to 1500 db, a net northward transport of 5×10^6 Sv was observed flowing into

the Bering Sea. This transport can be compared with the average annual figure of 4×10^6 Sv given by Favorite (1974). The flow was highly turbulent; geostrophic velocities in eddies were calculated in excess of 40 cm/sec and may have been two or three times this value for periods of short duration.

A series of direct-current observations were made from the vessel *Surveyor* at 51°35'N, 179°57'E (about 40 km northeast of the eastern end of Amchitka Island in about 1900 m of water) on June 3 to 6, 1963. A plot of directions and speeds at 10, 100, 200, and 300 m recorded each hour (commencing alternately at 10 m and at 300 m) indicate the complexity of flow evident in a data series for June 5 (Fig. 7). Isolated, abrupt, brief deviations from the direction of mean surface flow from 0 to 300 m occurred at 10 m; at 10 and 100 m; at 100 and 200 m; and at 100 and 300 m at various intervals. An extended period of flow (0400 to 1100 hr) with a consistently uniform easterly direction, opposite the offshore flow in the Alaskan Stream, was also indicated near this same location in the 1968 data (see Fig. 5). Velocities at all levels varied from about 25 to about 50 cm/sec, rarely in phase or with a specific relation to increasing depth; in fact, in several instances maximum velocities occurred at 300 m.

Fig. 6—Vertical sections of temperature and salinity from Semisopochnoi Island to 50°30'N.

GEOCHEMISTRY

Although temperature and salinity data are reasonably complete, geochemistry data for the Amchitka area are fragmentary even though such data could be informative not only as baseline information but also from a descriptive oceanography standpoint. The equilibrium between the saturation of CO_2 in surface water with respect to atmospheric CO_2 has great potential for explaining variations in the surface environment that are not evident from the distributions of temperature and salinity that reflect primarily large-scale physical processes. However, the analytical methods are complex, and only limited observations are available (Park, Gordon, and Alvarez-Borrego, 1974). If exchange with the atmosphere is restricted, cooling produces a decrease in the partial pressure of CO_2 and warming the opposite effect. Although photosynthesis by marine plants has the greatest effect on the reduction of CO_2 , several factors can contribute to supersaturation compared to atmospheric CO_2 , such as biochemical oxidation, addition of CO_2 -rich river waters, increase in the depth of the surface mixed layer, upwelling of CO_2 -rich subsurface waters, and upward divergence of deep water in cyclonic gyres. Although considerably more information is required to determine the individual effects of these processes, high variability in relative carbon dioxide concentrations between air and surface seawater exists in data from closely spaced stations in Amukta Pass near 171°W (Kelley, Longerich, and Hood, 1971). These data again reflect the intensity of turbulent processes near the passes. Nevertheless, Gordon et al. (1973) indicated that in late summer generally slightly supersaturated conditions occur all along the Aleutian chain, whereas CO_2 concentra-

tions in the central Bering Sea are undersaturated by over 60 ppm.

Geochemical studies conducted in February 1968 provided an information base on the concentration of major and trace elements and aided, where possible, in describing the general circulation in the vicinity of Amchitka Island. In addition to salinity and temperature, determinations were made of pH and magnesium, calcium, silicate, phosphate, strontium, and heavier metal ions (zinc, manganese, nickel, iron, and copper) (Table 3 and Fig. 8). The distributions are generally consistent with the circulation described on the basis of temperature and salinity distribution, and the scatter of values in the passes north of Amchitka (Fig. 8) suggests the strong mixing and movement of water through the Aleutian passes; offshore values are relatively uniform.

BIOLOGICAL OCEANOGRAPHY

Although relatively few biological observations in the immediate area of Amchitka Island have been made, both the Bering Sea and the North Pacific Ocean are regions of major fisheries and have an extended history of biological investigations.

McRoy, Goering, and Shiels (1972) discussed the work on primary productivity; Sanger (1974) reviewed the available data and obtained a value of $415 \text{ mg C m}^{-2} \text{ day}^{-1}$ as a best estimate of summer primary production in the Bering Sea. A schematic food chain for the Bering Sea area in summer (defined as June through November) shows examples of species representative of the kinds of organisms that would reasonably be expected to occur at several trophic levels (Fig. 9). Calculations

(Text continues on page 344.)

Fig. 7—Direct current measurements at $51^{\circ}35'N$, $179^{\circ}57'E$ on June 5, 1963 (USCGS *Surveyor*).

Table 3—Chemical Analysis of Water Samples

Master station	Geochemistry station	Depth, m	Temperature, °C	Salinity, ‰	Chlorosity (Chl)	pH (in situ temp.)	Silicate silicon, $\mu\text{g-at/liter}$	Magnesium, g/liter	(Mg/Chl) $\times 10^{-2}$	Calcium, g/liter	(Ca/Chl) $\times 10^{-2}$	Strontium, mg/liter	(Sr/Chl) $\times 10^{-4}$	Nickel, $\mu\text{g/liter}$	Iron, $\mu\text{g/liter}$	Copper, $\mu\text{g/liter}$	Zinc, $\mu\text{g/liter}$
1	1	2	4.7	32.681	18.51	7.88	25.4	1.54	8.32	0.527	2.85	5.29	2.86	1.2	0.9	11	
2	2	2	4.4	32.628	18.49	7.93	28.9	1.50	8.11	0.473	2.56	5.29	2.86	1.6	<0.1	13	
3	3	2	3.99	32.678	18.51	7.84	30.3	1.50	8.10	0.459	2.48	5.29	2.86	0.3	<0.1	5	
4	4	2	3.82	32.666	18.50	7.81	31.5	1.54	8.32	0.461	2.49	5.22	2.82	0.2	<0.1	7	
5	5	2	3.58	32.711	18.52	7.84	31.9	1.48	7.99	0.458	2.47	5.34	2.88	3.8	0.8	11	
6	6	2	3.71	32.657	18.50	7.81	30.8	1.42	7.68	0.450	2.43	5.33	2.88	1.2	0.9	10	
7	7	2	3.61	32.695	18.52	7.81	30.7	1.52	8.21	0.458	2.47	5.29	2.86	<0.1	1.9	5	
8	8	2	3.58	32.560	18.44	7.83	26.6	1.60	8.68	0.455	2.47	5.31	2.88	0.3	<0.1	8	
9	9	2	3.62	32.378	18.34	7.84	25.5	1.46	7.96	0.452	2.46	5.22	2.85	0.2	1.1	10	
10	10	2	3.63	32.438	18.37	7.85	29.7	1.52	8.27	0.453	2.47	5.31	2.89	0.2	1.0	9	
11	11	2	4.20	32.846	18.61	7.82		1.68	9.03	0.512	2.75	5.29	2.84	0.1	0.1	9	
12	12	2	3.8	32.726	18.54	7.72	39.7	1.48	7.98	0.472	2.55	5.22	2.82	0.1	0.9	10	13.7
13	13	2	3.65	32.921	18.65	7.78	42.4	1.50	8.04	0.469	2.51	5.22	2.80	0.1	1.0	8	9.0
		2	3.58	32.751	18.55	7.75	44.9	1.50	8.09	0.467	2.52	5.34	2.88	0.1	0.7	7	10.9
		1050	2.97	34.291	19.45	7.42	137.0	1.56	8.02	0.480	2.47	5.44	2.80	0.5	0.4	10	21.2
16	14	2	3.72	32.878	18.63	7.78	42.4	1.46	7.84	0.460	2.47	5.31	2.85				5.8
17	17	2	3.72	32.656	18.50	7.81	33.3	1.46	7.89	0.463	2.50	5.34	2.87	0.7	<0.1	5	9.4
21	15	2	3.75	32.686	18.52	7.94	35.8	1.48	7.99	0.460	2.48	5.29	2.86	1.8	0.8	10	13.0
26	16	2	3.58	32.82	18.59	7.77	43.9	1.58	8.50	0.460	2.47	5.31	2.86	0.6	0.8	8	11.7
32	20	2	3.61	32.651	18.59	7.77	38.3	1.44	7.79	0.450	2.43	5.34	2.89	0.3	0.2	12	12.4
34	21	2	3.45	32.841	18.60	7.68	47.6	1.50	8.06	0.456	2.45	5.29	2.84	0.1	<0.1	7	8.7
39	39	2	3.20	32.250	18.26		56.0	1.38	7.56	0.444	2.43	4.81	2.63	0.9	2.4	1	3.2
41	38	2	3.13	33.030	18.71		45.0	1.38	7.38	0.447	2.39	4.98	2.66	0.8	3.6	2	3.2
43	22	2	3.38	33.139	18.78	7.58	65.6	1.50	7.99	0.462	2.46	5.44	2.90	0.4	5.7	10	5.3
47	35	2	3.26	32.782	18.57	7.77	56.3	1.28	6.89	0.411	2.21	4.88	2.63	1.9	5.3		5.6
50	33	2	2.86	32.904	18.64	7.77	42.5	1.46	7.83	0.437	2.34	5.49	2.95	<0.1	0.8	12	4.6
	34	2000	2.09	34.559	19.60	7.64	160.0	1.48	7.55	0.469	2.39	5.44	2.78	0.8	5.4	11	19.8
55	31	2	2.82	32.90	18.64	7.76	55.5	1.48	7.94	0.443	2.38	5.26	2.82	0.1	1.0	9	8.9
	32	495	3.31	34.227	19.41	7.35	120.5	1.44	7.42	0.474	2.44	5.34	2.75	0.4	1.5	13	12.3
56	30	2	2.80	32.964	18.67	7.73	55.7	1.42	7.61	0.468	2.51	5.34	2.86	0.1	0.8	10	4.2
59	28	2	3.33	32.845	18.60	7.77	47.3	1.40	7.53	0.451	2.42	5.39	2.90	0.1	1.5	11	8.3
	29	150	3.76	33.565	19.02	7.56	84.1	1.50	7.89	0.459	2.41	5.16	2.71	0.3	1.6	9	12.2
63	27	2	3.02	32.996	18.69	7.75	55.7	1.44	7.70	0.454	2.43	5.26	2.81	0.3	1.6	12	11.3
67	36	2	3.15	32.841	18.60	7.69	39.3	1.48	7.96	0.482	2.59	5.19	2.79	1.3	6.2	2	1.6
	37	110	3.75	33.507	18.99		47.8	1.04	5.48	0.323	1.70	4.03	2.12	0.8	2.2	1	5.6
69	42	2	3.27	33.195	18.81		57.2	1.14	6.06	0.407	2.16	5.29	2.81	0.5	3.8		6.4
	43	170	3.35	33.342	18.89		59.3	1.08	5.72	0.439	2.32	5.03	2.66	3.6	4.9	1	1.6
71	23	2	3.45	33.186	18.80	7.68	69.7	1.48	7.87	0.465	2.47	5.34	2.84	0.7	1.4	9	9.0
75	25	2	3.14	33.250	18.84	7.64	77.3	1.50	7.96	0.460	2.44	5.44	2.89	0.4	3.3	11	11.0
	24	590	3.31	34.085	19.33	7.41	151.5	1.52	7.86	0.492	2.55	5.31	2.75	0.5	2.7	10	18.6
80	26	2	3.20	33.012	18.70	7.69	63.3	1.46	7.81	0.446	2.39	5.31	2.84	0.4	0.9	11	13.3
82	40	2	3.00	33.199	18.81		49.0	1.26	6.70	0.418	2.22	4.81	2.56	0.8	5.6	1	8.0
	41	405	3.50	33.836	19.18		75.9	1.00	5.21	0.397	2.00	4.76	2.48	1.9	2.8		7.2
86	44	2	2.80	33.06	18.73		61.5	1.14	6.09	0.463	2.47	5.13	2.74	1.7	5.7		25.8
93	45	2	3.35	33.253	18.84		61.5	1.20	6.37	0.489	2.60	5.24	2.78	1.1	2.2	1	10.9

Fig. 8—Surface distributions of phosphate-phosphorus ($\mu\text{g-at/liter}$), pH (in situ temperature), silicate silicon ($\mu\text{g-at/liter}$), magnesium (Mg/Chl) $\times 10^{-2}$, calcium (g/liter) and (Ca/Chl) $\times 10^{-2}$, strontium (Sr/Chl) $\times 10^{-4}$, and metals reported as zinc ($\mu\text{g/liter}$).

Fig. 9—Schematic of food chain and estimates of production for the Bering Sea area, June–November.

are also shown for an average daily primary production rate of $100 \text{ mg C m}^{-2} \text{ day}^{-1}$, which is more representative of estimated productivity in the North Pacific Ocean south of the island arc.

As part of the investigations on North Pacific Ocean and Bering Sea fisheries, the U. S. National Marine Fisheries Service conducted a series of investigations near Adak Island in the central Aleutians starting in 1957 which provided background data for investigations on primary productivity and zooplankton distribution. Observations in 1968 included measurements of primary productivity (carbon isotope method), chlorophyll *a* for standing phytoplankton stock, and other environmental variables, including incoming solar radiation. Zooplankton samples were analyzed for standing stock and for relative importance and distribution of the major zooplanktonic groups.

Primary Productivity

Motoda and Kawamura (1961) reported primary productivity from measurements taken about 80 km north and east of Amchitka Island during the summer of 1960. Although only surface values were obtained, productivity in the euphotic zone appeared to be several times higher in summer than in winter. Koblents-Mishke (1965) summarized measurements of primary productivity in the Pacific Ocean and estimated average daily production throughout the year in the Aleutian area to be 100 to $150 \text{ mg C m}^{-2} \text{ day}^{-1}$. The most comprehensive study of primary productivity in the Bering Sea is by Taniguchi (1969), who noted variations in primary production ranging from 160 to $630 \text{ mg C m}^{-2} \text{ day}^{-1}$. Larrance (1971) and McAlister et al. (1968) report extensively on productivity for the Aleutian area and subarctic waters south of the Aleutians. High productivity ranging from 350 to $460 \text{ mg C m}^{-2} \text{ day}^{-1}$ in March and as high as $2400 \text{ mg C m}^{-2} \text{ day}^{-1}$ for spring and summer was measured near Adak on the Bering Sea side. Observations in January and February 1967 (McAlister et al., 1970) south of the Aleutian Islands (162°W) showed much lower values, averaging $87 \text{ mg C m}^{-2} \text{ day}^{-1}$. These results are summarized in Table 4.

During the Amchitka observations of February 1968, productivity was measured at seven stations (McAlister et al., 1968) by the ^{14}C method of Steemann Nielsen (1952). Duplicate experimental bottles were held in an incubator with circulating seawater to provide ambient water temperature. The bottles were covered with neutral-light filters to simulate light intensities at the sample depths and were exposed to daylight. Each experiment lasted one-half day, from sunrise to local apparent

noon or from local apparent noon to sunset. Chlorophyll *a* and nutrient concentration were also measured at these stations (McAlister et al., 1968).

Observed concentrations of chlorophyll *a* ranged between 0 and 0.44 mg/m^3 . The wide fluctuations of chlorophyll *a* and nutrients in the surface layer indicated that the phytoplankton were not evenly distributed in the surface layer and suggested large-scale turbulence. A single dominant subsurface maximum of chlorophyll *a* occurred within the mixed layer when the layer did not extend to 100 m. Where the mixed layer extended below 100 m, chlorophyll *a* displayed several maxima and minima, none of which were distinctly dominant. The highest (14.5 mg/m^2) and lowest (3.8 mg/m^2) values (summed through the euphotic zone) of chlorophyll *a* were found at stations on the continental shelf south of Amchitka. The mean of chlorophyll *a* values was 9.0 mg/m^2 . The values of chlorophyll *a* did not differ significantly between offshore stations and those closer to shore. Mean productivity for all stations was $76 \text{ mg C m}^{-2} \text{ day}^{-1}$. The offshore stations averaged $102 \text{ mg C m}^{-2} \text{ day}^{-1}$.

All nutrient levels measured are adequate for phytoplankton growth. The regulating ecological factor appears to be light. Typically, light energy in higher latitude temperate zones is inadequate during winter to sustain an increase in phytoplankton populations. A comparison of the potential for production among stations was made assuming light as a limiting factor. Values calculated were generally similar at all stations, suggesting that, with equivalent light and standing stocks, the environment at the various stations will support about the same production.

Zooplankton

Zooplankton in the Subarctic Pacific Region are extremely important in the diet of baleen whales, the young of nearly all fishes, and some adult fish. Table 5 contains a fairly complete but not exhaustive list of dominant forms. Zooplankton studies have been made in the northwest North Pacific Ocean and adjacent seas by scientists from the Union of Soviet Socialist Republics (Heinrich, 1961; Bogorov and Vinogradov, 1968) and the United States (Aron, 1962). The biomass of zooplankton in the northwest Pacific Ocean during the spring and summer has been reported as 100 to 200 g/1000 m^3 (NORPAC Committee, 1960), 100 to 500 g/1000 m^3 (Bogorov, Beklemishev, and Vinogradov, 1961), and 100 to 2000 g/1000 m^3 (Bogorov and Vinogradov, 1968). Aron (1962) found that near the Aleutian Islands ten times more macrozooplankton were found in some samples than in others taken short distances away;

Table 4—Recent Estimates of Primary Production in the Water Column for Oceanic Waters Contiguous to Alaska (^{14}C method)*

Region	Daily rate, $\text{mg C m}^{-2} \text{ day}^{-1}$	Dates	Source
Bering Sea			
Bering Strait	4100	June 1969	McRoy et al. (1972)
Eastern Bering Sea	21	February 1970	McRoy et al. (1972)
Aleutian area			
Unimak Pass area	243	June 1968 and 1970	McRoy et al. (1972)
	87	January–February 1967	McAlister et al. (1970)
Amchitka Island area	38 to 45	February 1968	McAlister et al. (1968)
Adak Island coast	686	June–July 1967	Larrance (1971)
	581	August 1967	
	404	September 1966	
Adak Bay	350 to 460	March 1966	Larrance (1971)
	840 to 2400	Late spring–summer	
Central subarctic domain			
Subarctic waters south to Adak Island	133	February	Larrance (1971, Fig. 5, p. 604)
	325	March	
	280	May	
	327	June	
	250	July	
	207	August	
	240	September	

*Adapted from Sanger (1974).

large catches were obtained preferentially in areas of high stability in the water column.

Zooplankton samples were collected with a Pacific Oceanic Group (POG) net at 35 night stations in February 1968. Two replicate tows, 5 to 10 min apart, were made at each station. Vertical tows from 150 to 0 m were made at each station, depth permitting, and were retrieved at a rate of 2 m/sec. Total time required to retrieve 150 m of cable was 75 ± 3 sec. Where the depth of the bottom did not permit tows to 150 m, shallow tows were made by lowering the net to approximately 6 m above the bottom. The rate of retrieval for shallow tows was also 2 m/sec. Geographic position, date, time of tow, depth range, and meter revolutions obtained from a flowmeter located at the side of the net mouth were recorded for all collections. Samples were preserved at sea in 5% Formalin.

Displacement volumes were measured, and taxonomic groups were sorted and counted at the Northwest Fisheries Center, National Marine Fisheries Service, Seattle. Samples were subdivided for taxonomic enumeration into subsamples of 300 to 500 animals. Most subsamples were $\frac{1}{8}$ splits but ranged from $\frac{1}{4}$ to $\frac{1}{16}$ of a sample. The total numbers of organisms were counted in six samples (4, 28, 36, 38, 54, and 68) as a check on the accuracy of subsampling.

Zooplankton volume near Amchitka Island ranged from 9.6 to 107 ml/1000 m^3 with a mean of 40.7. Data from the U. S. National Marine Fisheries Service cruises in 1966 and 1967 indicated volume values in the Alaskan Stream south of Adak Island which ranged from 10 to 70 ml/1000 m^3 in winter to 400 to 500 ml/1000 m^3 in summer. Thus zooplankton volume in the area south of the Aleutian Islands may change seasonally by an order of magnitude. Values for displacement volume of replicate samples varied as much as 166%. This variation is probably due to a patchy distribution of zooplankton and again represents effects of large- and medium-scale turbulence.

Numerically, copepods dominated the zooplankton, contributing 85.2% to the samples; other main zooplankton groups are shown in Table 6. Analysis of variance showed a significant variation ($p < 0.05$) in abundance between stations for all groups except ostracods. The maximum variation in biomass (9.6 to 107 ml/1000 m^3) was observed across the Alaskan Stream south of Amchitka. Biomass was lowest near the center of the Alaskan Stream but increased near its northern and southern boundaries (Fig. 10). Southward of this flow, the abundance of all organisms was relatively low except for euphausiids and amphipods. Total abundance of zooplankton organisms followed a distributional pattern similar to the total biomass except

Table 5—Dominant Species of Zooplankton

Subclass: Copepoda	Family: Oncaeidae
Order: Calanoida	Genus and Species:
Family: Calanidae	<i>Oncaea media</i>
Genus and Species:	Order: Harpacticoida
<i>Calanus plumchrus</i>	Family: Ectinosomidae
<i>Calanus cristatus</i>	Genus and Species:
<i>Calanus marshallae</i>	<i>Microsetella norvegica</i>
<i>Calanus glacialis</i>	Subclass: Malacostraca
Family: Eucalanidae	Order: Euphausiacea
Genus and Species:	Family: Euphausiidae
<i>Eucalanus bungii</i>	Genus and Species:
<i>Eucalanus californicus</i>	<i>Euphausia pacifica</i>
<i>Eucalanus elongatus hyalinus</i>	<i>Euphausia gibboides</i>
Family: Paracalanidae	<i>Thysanoessa gregaria</i>
Genus and Species:	<i>Thysanoessa inermis</i>
<i>Paracalanus parvus</i>	<i>Thysanoessa inspinata</i>
Family: Pseudocalanidae	<i>Thysanoessa longipes</i>
Genus and Species:	<i>Thysanoessa spinifera</i>
<i>Pseudocalanus minutus</i>	<i>Tessarabrachion oculatus</i>
<i>Clausocalanus arcuicornis</i>	<i>Nematoscelis difficilis</i>
<i>Clausocalanus pergens</i>	<i>Nematobrachion flexipes</i>
<i>Ctenocalanus vanus</i>	<i>Stylocheiron maximum</i>
Family: Actideidae	Order: Amphipoda
Genus and Species:	Suborder: Gammaridae
<i>Actideus pacificus</i>	Family: Lysianassidae
<i>Gaetanus armiger</i>	Genus and Species:
Family: Euchaetidae	<i>Cyphocaris challengerii</i>
Genus and Species:	Suborder: Hyperiididae
<i>Pareuchaeta elongata</i>	Tribe: Physocephalata
Family: Scolecithricidae	Family: Vibiliidae
Genus and Species:	Genus and Species:
<i>Scolecithricella minor</i>	<i>Vibilia australis</i>
Family: Metridiidae	Family: Hyperiididae
Genus and Species:	Genus and Species:
<i>Metridia lucens</i>	<i>Hyperia medusarum</i>
<i>Pleuromamma abdominalis</i>	<i>Hyperoche mediterranea</i>
Family: Centropagidae	<i>Parathemisto pacifica</i>
Genus and Species:	Family: Anchylomeridae
<i>Centropages abdominalis</i>	Genus and Species:
Family: Lucicutiidae	<i>Primno macropa</i>
Genus and Species:	Family: Lycaeidae
<i>Lucicutia flavicornis</i>	Genus and Species:
Family: Candaciidae	<i>Tryphaena malmii</i>
Genus and Species:	Family: Oxycephalidae
<i>Candacia columbiae</i>	Genus and Species:
<i>Candacia bipinnata</i>	<i>Streetsia challengerii</i>
Family: Acartiidae	Phylum Chaetognatha (Tokioka classification)
Genus and Species:	Class: Sagittoidea
<i>Acartia clausi</i>	Order: Phragmophora
<i>Acartia longiremis</i>	Family: Eukrohniidae
Order: Cyclopoida	Genus and Species:
Family: Oithonidae	<i>Eukrohnia hamata</i>
Genus and Species:	Order: Aphragmophora
<i>Oithona helgolandica</i>	Family: Sagittidae
<i>Oithona spirostris</i>	Genus and Species:
<i>Oithona</i> sp.	<i>Parasagitta elegans</i>
	<i>Flaccisagitta scrippsae</i>

in the nearshore waters south of Amchitka Island where biomass was high and total abundance low. Except for pteropods and amphipods, all taxonomic groups were most abundant at the bound-

aries of the Alaskan Stream. Distribution patterns for select zooplankton are shown in Figs. 11 to 18.

The general north-south distributional patterns of biomass may be summarized as follows:

low north of Amchitka Island in waters of Bering Sea origin; high in nearshore waters south of Amchitka Island; high near the northern boundary of the Alaskan Stream, decreasing in the axis of flow and increasing near the southern boundary; and low south of the Alaskan Stream.

Table 6—Percent Composition of Zooplankton Volume

Item	Percentage	Item	Percentage
Copepods	85.2	Euphausiids	1.5
Chaetognaths	5.2	Pteropods	1.0
Amphipods	2.4	Ostracods	0.9
Cnidarians	1.8	Remaining	
Larvaceans	1.6	zooplankton	0.4

eastward flow to the north of the island arc. Second, the island is adjacent to a major passage, Amchitka Pass, through which north-south excursions override and penetrate well into the east-west flows. Third, it is situated at the junction of the Alaskan and western subarctic gyres, the former having a predominant southward flow and the latter a predominant northward flow in this area. Finally, it is at the southernmost part of the island arc; thus flows along bathymetric contours are subject to different geophysical effects east and west of the island.

There is no evidence of local upwelling; thus chemical nutrients must be advected laterally into

Fig. 10—Zooplankton volume in oceanic and coastal waters (ml per 1000 m³).

CONCLUSIONS

Although broad easterly currents (Kuroshio and Subarctic Currents) dominate flow in the central North Pacific Ocean, the circulation near Amchitka Island is directly influenced by the complex patterns of exchange and mixing between North Pacific Ocean and Bering Sea waters in the passes of the Aleutian Islands. A number of factors contribute to the turbulent flow regime characteristic of the area around Amchitka Island. First, the island is located in what may be considered a shear zone between the westward flow to the south and

the area. Nevertheless, concentrations are not limiting primarily because of turbulent mixing and stirring along the island arc. As a result of turbulence, there is a 1 to 4°C decrease in surface temperatures in the coastal regime compared to offshore oceanic conditions which is usually manifested as a temperature frontal zone near the northern boundary of the Alaskan Stream.

The general biological characteristics and processes are similar to those found throughout the Subarctic Pacific Region. The wide variations from station to station are characteristic of large-scale turbulence; maximum concentrations of organisms

(Text continues on page 352.)

Fig. 11—Estimated abundance of cnidarians per 1000 m³ of water, oceanic and coastal waters.

Fig. 12—Estimated abundance of ostracods per 1000 m³ of water, oceanic and coastal waters.

Fig. 13—Estimated abundance of pteropods per 1000 m³ of water, oceanic and coastal waters.

Fig. 14—Estimated abundance of copepods per 1000 m³ of water, oceanic and coastal waters.

Fig. 15—Estimated abundance of euphausiids per 1000 m³ of water, oceanic and coastal waters.

Fig. 16—Estimated abundance of chaetognaths per 1000 m³ of water, oceanic and coastal waters.

Fig. 17—Estimated abundance of larvaceans per 1000 m³ of water, oceanic and coastal waters.

Fig. 18—Estimated abundance of amphipods per 1000 m³ of water, oceanic and coastal waters.

are associated with fronts between water masses, lowering of temperature, and erosion of vertical stability. Violent movements associated with the inshore turbulent regime affect primary production directly as well as the movement and concentrations of zooplankton herbivores.

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Ecology of Marine Algae*

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The rocky shores of Amchitka Island are densely carpeted by marine algal communities, which, beyond the coast exposed by the tides, are characterized by extensive floating kelp beds. An unusual feature of the intertidal area of the southeastern third of the island is the occurrence of wide, often extremely flat, rock benches at about mean tide level.

The littoral region is characterized by a supralittoral fringe area with *Prasiola*, *Rhodochorton*, and *Porphyra*—*Ulothrix* zones and a midlittoral area with *Fucus*, *Hedophyllum*, and *Alaria* zones. Many species distributions are strongly influenced by the benches, being correlated with horizontal distance perpendicular to the shore. The presence of *Hedophyllum* and *Fucus* zones indicates more protected conditions than might have been expected. It is suggested that the bench topography and offshore kelp beds provide an exposure gradient across the intertidal area. The sublittoral fringe is characterized by a zone of *Laminaria longipes*. Most littoral algae occur throughout the year but exhibit growth in the spring and summer. The *Porphyra*—*Ulothrix* zone and the *Halosaccion* association appear in spring and reach a peak of development in the summer. Plots in the intertidal region denuded of all organisms exhibited colonization by a sequence of diatoms and filamentous algae, leafy green algae, and, last, larger red and brown algae. Initial settlement was seasonal and occurred fastest in exposed areas at low levels. The removal of only the kelp canopy gave similar results, but colonization occurred more quickly and was influenced by the remaining understory vegetation.

The most conspicuous element of the sublittoral flora is *Alaria fistulosa*, which forms the extensive floating kelp beds. Down to 20-m (66-ft) depth, the bottom is densely covered with species in the genera *Laminaria*, *Alaria*, *Cymathere*, *Agarum*, and *Thalassiosiphon*. A third level of vegetation is formed by populations of *Ptilota*, *Hypophyllum*, *Cirrularia*, and *Constantinea*. Finally, crustose coralline algae, particularly *Clathromorphum nereostratum*, and the green alga *Codium ritteri* dominate rocky bottoms below 20 m (66 ft). The predation of the sea otter on invertebrate herbivores is undoubtedly a major factor in the formation of such dense algal communities.

The Milrow nuclear test affected about 4 ha (10 acres) of littoral vegetation when an uplift of about 12 cm (5 in.) occurred on an intertidal rock bench. Mortality was extensive in the upper portions of all zones 6 months after the disturbance, and significant changes were still occurring when last observed, 3½ years after Milrow. The Cannikin nuclear test resulted in uplifting up to a maximum of 1 m (3 ft). Mortality of littoral vegetation was severe along 1.9 km (1.2 miles) of coast, including areas with 0.5 to 1 m of uplift. Moderate mortality was observed along an additional 1.5 km (1 mile) of coast, and mortality was detectable along a further 2.7 km (1.7 miles) of coast. Significant changes in vegetation were reported to be occurring nearly 3 years after Cannikin. A normal littoral vegetation will eventually return to both the Milrow- and Cannikin-disturbed areas. The lifting of some rock benches above the midlittoral area as a result of the Cannikin test has resulted in a significant permanent reduction in area available to most littoral species.

The benthic marine algae, commonly known as seaweeds, grow luxuriantly around the rocky coasts of Amchitka Island. These plants form a conspicuous covering on rocks uncovered by low tides. Floating kelp beds, consisting of plants that are attached to the rocky bottom, occupy large areas of the ocean surface surrounding the island. As primary producers these kelp plants are a major

source of food for primary consuming organisms, particularly marine invertebrates.

The history of phycological research in the North Pacific Ocean and our studies of the physical environment, the structure of marine algal communities, biological interactions, and the effects of underground nuclear testing on the algal communities of Amchitka Island are reviewed in this chapter.

HISTORICAL REVIEW

Until 1967, the starting point for studies reported in this chapter, the Aleutian marine algae were practically unknown. Therefore the floristic

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relationships of the Amchitka algal flora are best obtained by reviewing the literature of surrounding areas of the North Pacific Ocean. A comprehensive review of the Russian literature is given because most of the articles are practically unknown or unavailable in North America.

Aleutian Islands

The first publication on marine algae from the Aleutian Islands (Mertens, 1829) resulted from the expedition of the Russian ships *Seniavin* and *Moller*, which were under the command of Lütke. The famous "Illustrationes Algarum" (Postels and Ruprecht, 1840) presented the full treatment of the marine algae collected on this expedition by Postels, Mertens, and Kastalsky. In the Aleutian Islands marine algae were collected at Unalaska Island only. Further records of Aleutian marine algae, again limited to Unalaska Island, were published by Setchell and Gardner (1903). Algal specimens from the western Aleutian Islands, including the first collections from Atka, Amchitka, and Agattu Islands, were gathered by Kobayashi from May to August 1931 and were reported on by Okamura (1933). Brief comments on the marine and land plant communities of the Aleutian Islands were made by Tatewaki and Kobayashi (1934). Field work was conducted by Tatewaki in 1929 on Attu, Amchitka, and Atka Islands and by Kobayashi in 1931 on Attu, Amchitka, Atka, Umnak, and Unalaska Islands. The account of the marine vegetation, comprising 21 species of marine algae, includes no details on localities; thus it is impossible to determine on which islands each species was observed. Collections of marine algae from Attu, Shemya, Adak, and Unimak Islands were made in 1960 as part of a large study of the North Pacific algal distributions by Scagel (1962; 1963). These collections, deposited in the Phycological Herbarium of the University of British Columbia, were later used by students and associates of Scagel in monographic studies of the genera *Hedophyllum* (Widdowson, 1965), *Laminaria* (Druehl, 1968), *Alaria* (Widdowson, 1971a; 1971b), *Porphyra* (Conway et al., 1976), and *Ulva* (Tanner, in preparation). Druehl (1970) discussed the distribution of the Laminariales in the North Pacific Ocean. Only three species of marine algae had been reported from Amchitka Island prior to our studies.

Several other publications, although not dealing directly with the Aleutian Islands, are important either taxonomically or geographically in studies of the marine algae of Amchitka Island. Probably the most pertinent of these are the publications of Kjellman (1889) on the algae of the

Bering Sea and Guryanova (1935), Kardakova-Prezhentsova (1938), and E. Zinova* (1940) on the marine algae of the Commander Islands.

The publication by Kjellman (1889) resulted from collections made on the *Vega* expedition in the Bering Sea from July 20 to Aug. 19, 1879. These collections were made at St. Lawrence Bay and Konyam Bay on the Chukotski Peninsula, Union of Soviet Socialist Republics; Port Clarence, on the Seward Peninsula, Alaska; and Bering Island, one of the Commander Islands. This work is still an important taxonomic reference, and it is the only work in which the distribution of the marine algae of the Bering Sea is treated comprehensively.

Guryanova (1935) discussed the history of scientific research, geology, climate, oceanography, and biology of the Commander Islands and made extensive observations on the marine algal vegetation of Bering Island from November 1930 to June 1931. The distribution of marine plants and animals on Bering Island, although treated in detail, was not studied with quantitative methods. A more detailed study of the distribution of the seaweeds of the Commander Islands was undertaken by Kardakova-Prezhentsova from 1928 to 1932 (Kardakova-Prezhentsova, 1938). A comprehensive list, containing 174 species of marine algae collected at the Commander Islands from 1871 to 1932, was compiled by E. Zinova (1940).

Eastern Bering Sea

Several short papers have dealt with marine algae from the eastern Bering Sea. Setchell (1899) published a short list of marine algae collected at the Pribilof Islands and Chihara (1967) reported on some marine algae collected at Cape Thompson, Alaska. From Izembek Lagoon, on the north coast of the Alaska Peninsula opposite Cold Bay, McRoy (1968) collected the Eurasian alga *Fucus inflatus* f. *latifrons* and Biebl (1970; 1972) studied the temperature resistance of a few local algal species.

Pacific North America

Research on marine algae east of the Alaska Peninsula, along the Pacific North American coast, has resulted in many publications. The importance of these studies to the Amchitka flora is generally

*Spelled E. S. Sinova as transliterated on the original publications. This spelling is generally used in the phycological literature. To conform with transliteration standards now accepted, we have spelled her name with a "Z" in this paper. So that this author will not be confused with A. D. Zinova, a niece, who also published on marine algae, the first initial is used in citations throughout this chapter.

inversely related to their distance from the Aleutian Islands. The Harriman Alaska Expedition collected 207 species of marine algae at Victoria, British Columbia, and at several localities along the southern coast of Alaska as far west as the Shumagin Islands (Saunders, 1901). Scagel's annotated list of marine algae of British Columbia and northern Washington (Scagel, 1957) has recently been superseded by his monograph of the Chlorophyceae (Scagel, 1966) and revised lists and keys for the Phaeophyceae (Widdowson, 1973) and Rhodophyceae (Widdowson, 1975) which cover the same geographical area. These publications contain information on many species that occur in the Aleutian Islands. A guide to the literature and distributions of Pacific benthic algae, including Alaska, was published by Dawson (1961). Johansen (1971) reported on the effects of the Alaska earthquake of 1964 on intertidal benthic algae in Prince William Sound. Although the littoral marine algae were destroyed in some localities, 120 taxa of macroalgae were collected, and 17 of these represented new records for the area.

Russian Studies

Bibliographies of the Russian literature on marine algae published from 1900 to 1940 have been compiled by Gaïdukov (1901), Elenkin and Ol' (1929; 1935; 1950a; 1950b), Gollerbach et al. (1966), and Krasavina (1968). A taxonomic cross-index to these bibliographies, spanning the years 1737 to 1960, was compiled by Gollerbach and Krasavina (1971). A short history of Pacific Russian scientific investigations was given by Komarov (1962). Nearly all the Russian taxonomic studies on marine algae have been carried out at the Komarov Botanical Institute in Leningrad (St. Petersburg in the older literature) by Elena S. Zinova and later by her niece, Anna D. Zinova. A history of the Institute in English was recently published (Shetler, 1967).

Eastern Kamchatka

The earliest records of marine algae from Kamchatka (Komarov, 1962) appear to have been those of Gmelin (1768), which were based on specimens that had accumulated at the Imperial Academy in St. Petersburg. Gmelin classified into the Linnean algal genera *Fucus* and *Ulva*, fifteen species from Kamchatka that were collected in part by Steller and "Kraschenninikow." Most of the later studies on marine algae on this coast took place in Avachinskaya Bay. The first of these studies was carried out in 1908 and 1909 as part of

the Kamchatka Expedition of F. P. Ryabushinski. Savich" (1914) described the algal vegetation in the bay. The taxonomy of Savich's specimens was determined by Voronikhin (1914). The area was studied again in 1929 and 1930 by a zoological expedition, and the algal specimens were described by E. Zinova (1933). A few species in the red algal family Delesseriaceae were also recently described from the area (A. Zinova, 1965). In northeastern Kamchatka, eight marine algae were collected by Takayama in August 1923 at Korf (Baron Korfe), on the northwest coast of Korf Zaliv (Okamura, 1928). The littoral and sublittoral algae from Anadyrskiy Bay were described by Vinogradova (1973a; 1973b). A study of the littoral and sublittoral algae of Karaginskiy Island was carried out in 1930 (Kongiser, 1933). Further studies of marine algae from southeastern Kamchatka included an expanded list of species (E. Zinova, 1954a) and a detailed description of littoral zonation (Spasskiĭ, 1961).

Kurile Islands

An extensive account in English of the marine algae of the Kurile Islands was published by the Japanese phycologist Nagai (1940; 1941). Subsequently several Russian papers have been published. The distribution of the fauna and flora of the littoral region of the Kurile Islands was described by Kusakin (1961). Several taxonomic papers have also appeared that are based on specimens of Laminariaceae (Gusarova and Petrov, 1970; 1972) and various red and brown algae (Gusarova, 1972).

Okhotsk Sea

The first major paper on the marine algae of the Okhotsk Sea was the classical phycological treatise "Tange des Ochotskischen Meeres" (Ruprecht, 1851). This work was based on specimens that had accumulated in the herbarium of the Imperial Academy of St. Petersburg since Gmelin's time. Most of these specimens had been collected in 1807 by Redovski (a few possibly also by Steller) in the eastern Okhotsk Sea and later by Middendorff in the Shantar Islands. In this work, which is rare and generally unavailable in North America, 57 species of algae were reported. A more detailed study of the Shantar Islands algal flora was made by E. Zinova (1930). A brief description of the littoral zonation of the Okhotsk Sea was given by Ushakov (1951). From 1905 to 1945 the southern portion of Sakhalin Island, which separates the Okhotsk Sea from the Sea of Japan, was under the jurisdiction of Japan. During this period

extensive studies of marine algae were conducted by various Japanese workers, and a total of 182 species were recorded from the area (Tokida, 1954). Taxonomic papers on *Laminaria* (Petrov and Vozzhinskaya, 1970; A. Zinova, 1964; 1969), *Cystoseira* (Petrov, 1966), *Sargassum* (Petrov, 1968), *Rhodomenia* (Blinova and A. Zinova, 1967), and *Rhodoglossum* (Perestenko, 1967) were published. Vozzhinskaya (1960b) described some endophytic algae. The comprehensive Russian paper on the algae of the Okhotsk Sea (E. Zinova, 1954b) has also been further augmented by papers covering several algal groups (Blinova, 1968; Blinova and Gusarova, 1970; Vozzhinskaya, 1960a; 1964a; 1965a; 1967; Vozzhinskaya and Vishnevskaya, 1968).

Ecological studies of marine algae, dealing mainly with distributions, associations, and biomass, have also been carried out in the Okhotsk Sea. The distribution of a few littoral algae was described by Ushakov (1951). In 1954 and 1955 an extensive study of the littoral and sublittoral marine algae of Sakhalin Island was carried out by the Far Eastern Coastal Expedition of the Institute of Oceanology (Shchapova, Mokievskii, and Pasternak, 1957; Shchapova and Vozzhinskaya, 1960; Vozzhinskaya, 1964b). In the littoral region quantitative samples were taken along transects, and in the sublittoral region qualitative samples were obtained by grabs, trawls, and diving. The results of these studies are available in English (Shchapova and Vozzhinskaya, 1960; Vozzhinskaya, 1964b). Littoral and sublittoral community studies were carried out in the northern Sea of Okhotsk, along the western coast of Kamchatka, by Vozzhinskaya (1965b) and Vozzhinskaya and Blinova (1970). The marine vegetation of the Shantar Ostrovov was discussed by Vozzhinskaya and Selitskaya (1970b). Finally, the distribution and biomass throughout the Okhotsk Sea was described by Vozzhinskaya and Selitskaya (1970a).

Phytogeography

Several Russian papers have dealt with phytogeography in which more than one of the above geographical regions have been discussed. Shchapova (1946) discussed the distribution of some Phaeophyceae in the Pacific Ocean, and later (Shchapova, 1948) she considered the distribution of the Laminariales at greater length. The marine algal resources of the Soviet Union from the point of view of utilization were compared by Kireeva (1965). Finally, phytogeographical changes of littoral biota from the Bering Sea to Sunda Strait were discussed by Mokievskii (1967).

Japanese Studies

The literature on Japanese marine algae is too extensive to review here. A recent book on this subject (Tokida and Hirose, 1975) gives a good review of Japanese ecological work. Taniguti (1962) gives an extensive account in English of phytosociological studies that he carried out in the littoral region along the entire Japanese coastline. Other important papers are in the numerous publications of various Japanese universities and the *Bulletin of Japanese Society of Phycology* (sic).

The preceding review illustrates the extensive research that has been carried out on marine algae in the North Pacific Ocean and also points out the lack of information from the Aleutian Islands. We hope that our studies will partially fill this gap in our knowledge of North Pacific marine algae.

Amchitka Studies

Beginning in 1967, F. C. Weinmann made extensive collections of marine algae around Amchitka. He also studied the distributions and community structure of littoral algae along two transects, one on the Pacific Ocean coast (Makarius Bay,* designated T-1) and one on the Bering Sea coast (Square Bay, designated T-2). (See Geological Survey map in the pocket at the back of this volume.) The results of these transect studies constituted a master's thesis (Weinmann, 1968) and a Battelle Columbus Laboratories publication (Weinmann, 1969). Photogrammetry was used in continued study of Weinmann's transects, and a third transect at Rifle Range Point (designated T-3) was established in 1969 (Burgner et al., 1969). A summary of results to 1969 was reported at a Symposium on Amchitka Bioenvironmental Studies held at the 21st Annual Meeting of the American Institute of Biological Sciences and was subsequently published (Lebednik, Weinmann, and Norris, 1971).

Extensive analysis of the T-3 transect and comparison of algal weight and cover relationships (Burgner et al., 1971), continued sampling at the T-1 and T-2 transects (Burgner and Nakatani, 1972; Nakatani et al., 1973), and denudation of plots of selected algae (Nakatani et al., 1973; Palmisano, 1975) were three additional studies completed at Amchitka. Effects of the Milrow underground nuclear test on marine algae were reported by Burgner, Isakson, and Lebednik (1970), Lebednik (1973), Nakatani et al. (1973), and Nakatani and Burgner (1974). The effects of

*Also known as St. Makarius Bay.

Table 1—Sampling Dates of Transects and Test-Effects Study Areas

Date	T-1*	T-2*	T-3*	IA-1*	IA-2*	IA-3*	Coastal walk*	Colonization studies (3 areas)*
†March to April 1968	W	W						
†May 1968	O	O						
August 1968	P	P						
March 1969	P	P						
May 3 to 7, 1969			P, W					
June 1969	P	P						
Oct. 2, 1969 (Milrow test)								
Apr. 21, 1970				P				
May 21, 1970				P				
August 1970					P	P		
September 1970				P				
December 1970	P	P						
March 1971				P				P
May 1971								P
July 1971				P	P	P	O	P
August 1971								P
September 1971								P
October 1971				P	P	P		
Nov. 6, 1971 (Cannikin test)								P
December 1971				P	P	P		
February 1972	P	P		P	P	P		P
April 1972	P	P		P	P	P	O	P
June 1972	P	P		P	P	P		P
August 1972	P	P		P	P	P		P
October 1972	P	P		P	P	P		P
December 1972								P
April 1973	P	P		P	P	P	O	P
August 1973	P	P		P	P	P		
‡May 1974					P	P		
‡August 1974					P	P		

*P, photographic sample; W, dry-weight sample; and O, visual observations.

†Samples taken by F. C. Weinmann.

‡Samples taken by FRI staff; reported in Kirkwood (1974; 1975).

the Cannikin test were reported by Nakatani et al. (1973) and Nakatani and Burgner (1974). From August 1968 to August 1973, the preceding studies were conducted by Lebednik. The experimental denudation studies were conducted by Palmisano (1975). Subsequent observations of Milrow and Cannikin effects as reported in Kirkwood (1974; 1975) were made by other FRI investigators. The littoral sampling program is summarized in Table 1.

From the beginning of the marine algal studies, it was apparent that many poorly known and undescribed species were common in the Amchitka flora and that a comprehensive taxonomic study would produce a valuable contribution to our knowledge of the marine algal flora of the North Pacific Ocean. In 1968, R. E. Norris, F. C. Weinmann, and M. J. Wynne agreed to undertake a taxonomic study of all the macroscopic algae of Amchitka. Subsequently Lebednik joined the project and undertook taxonomic studies of the

coralline algae. Weinmann continued his graduate career elsewhere. Extensive collections were made for this taxonomic study in the littoral and sublittoral regions from 1967 through 1973.

In the first contributions to this study, Wynne described the Delesseriaceae (Wynne, 1970a; 1975), Bonnemaisoniaceae (Wynne, 1970b), and *Porphyra* species of Amchitka (Wynne, 1972), all members of the red algae. An ecological study on algal canopy interactions in the sublittoral region was reported by Dayton (1975).

A number of later papers have been based, in part, on collections made at Amchitka. Wynne (1971) merged the brown algal genera *Analipus* and *Heterochordaria*. Lebednik presented a monographic treatment of the coralline genera *Clathromorphum* and *Mesophyllum* on the Pacific Coast of North America (Lebednik, 1974; 1975; 1977) and an evolutionary scheme for the Corallinaceae and Cryptonemiales (Lebednik, in press, a; in press,

c). The algal communities of the Aleutian Islands were reported by Lebednik (in press, b). Live material of crustose red algae collected on Amchitka and sent to the laboratory of Dr. J. West contributed data for three papers dealing with hybridization and development in culture (Polanshek, 1975; Polanshek and West, 1976; DeCew and West, in press).

Three genera and eight species of red algae from Amchitka have been newly described in the preceding papers.* Table 2 is a list of species identified to date. The taxonomic studies are continuing, and we hope that the entire macroscopic algal flora will be described in future publications.

PHYSICAL FEATURES OF THE ENVIRONMENT

The topography of the Amchitka littoral region, which is important in the determination of the distribution of littoral algae, is unusual and deserves description. An aerial view of a segment of coastline at low tide (Fig. 1) shows two extensive rocky flats (B), dissected by large channels (C), bordered landward by boulder strands and separated by a sandy beach and the mouths of two streams (S). Such stream mouths usually indicate a sand or gravel trough (T) projecting seaward through and beyond the littoral rock flats (Powers, Coats, and Nelson, 1960; Lebednik, Weinmann, and Norris, 1971). The littoral rocky areas are mainly characterized by a feature termed rock benches (Powers et al., 1960), intertidal platforms (Morris, 1971), or strandflats (Everett, Chap. 8, this volume). At Bird Cape, at East Cape, at some other promontories, and in the northwest third of the island these benches are lacking, but, in the southeastern third of Amchitka, they are a dominant feature, occurring where there is a bedrock of permeable fine-grained breccia (L. M. Gard, personal communication; Powers et al., 1960). Sand, cobble, or boulder strands, which are mostly associated with stream mouths, occur for short intervals.

Figure 2 is an idealized schematic section through a segment of coast where an intertidal bench is present. The landward margin is commonly a sheer cliff 20 to 30 m (60 to 100 ft) high surmounted by a mantle of tundra. At the foot of the cliff, huge blocks of cliff fragments and

isolated sea stacks arise out of a beach of well-rounded gravel or cobbles. These blocks and stack bases as well as the larger boulders and cobbles and sometimes the cliff face itself constitute the substrate for supralittoral fringe populations of *Porphyra*, *Prasiola*, *Bangia*, and *Ulothrix*. Midlittoral vegetation begins at the abrupt transition from gravel beach (frequently enriched by great piles of drift algae) to rock bench covered by silt as much as 5 cm (2 in.) thick which is stabilized by several sabellid polychaete species (Fig. 3). In the winter this silt blanket may be eroded away, exposing a rock surface sparsely occupied by the crustose coralline alga, *Clathromorphum circumscriptum*. Frequently this area is lower than the seaward portion of the bench; consequently seawater may cover the rock bench at low tide. This depressed area is referred to as the moat.

The greatest fraction of the littoral region is occupied by the next seaward component, the emergent intertidal rock benchflat (Figs. 1 and 2). The midlittoral vegetation reaches its greatest development here and is readily accessible; most of our research was conducted in this area. The benchflat lies approximately at mean sea level, varying 2 to 3 m (7 to 10 ft) above and below. Powers et al. (1960) report the bench width to be about 15 m (50 ft) on the average, with an occasional segment as wide as 400 m (1300 ft). This bench area is topographically diverse. It may be an extremely flat surface with a pure stand of a single algal species or it may be a surface undulating a meter or more in height and with a diverse vegetation. Cobble-lined channels (Fig. 1), usually connected with the sea even at low tide, may dissect the surface, and local depressions may form tide pools (but tide pools are uncommon along the whole coastline). Both channels and tide pools have a vegetation that is mostly sublittoral in composition. A microtopographical feature of significance is the occurrence of small or large masses of harder rock 5 to 100 cm (2 to 40 in.) in diameter that project above the plane of the softer breccia. Often an isolated clump of *Fucus distichus* on the bench will mark the presence of one of these protruding rocks. The final feature, common but not present on all benches, is an elevated ridge or rampart on the seaward edge of the bench (Fig. 2). The rampart is typically 1 to 2 m (2 to 7 ft) higher than the bench and tends to have an irregular outline with small tide pools in depressions. Within a small distance along its length, a rampart may show a wide range of littoral algal species as well as a sharp difference between species on the exposed seaward face and the protected landward face, the former being the most exposed habitat of the bench region.

*The new genus *Mikamiella* Wynne has been proposed but not validly published (Wynne, 1975).

Fig. 1-- Aerial photograph of a portion of the Bering Sea coastline studied on July 21, 1971.
 (Photograph taken on Sept. 2, 1971, by Battelle Memorial Institute).

Table 2—Marine Algae of Amchitka Island, Alaska, as of June 1973

Phylum Chlorophycophyta	Order Nemaliales
Order Ulotrichales	<i>Pleuroblepharis japonica</i> (Okam.) Wynne
<i>Enteromorpha</i> sp.	<i>Rhodochorton purpureum</i> (Lightfoot) Rosenv.
<i>Monostroma arcticum</i> Wittrock	Order Cryptonemiales
<i>Monostroma fuscum</i> (P. et R.) Wittrock	<i>Bossiella cretacea</i> (P. et R.) Johansen
<i>Ulothrix flacca</i> (Dillwyn) Thuret	<i>Callophyllis flabellulata</i> Harvey
<i>Ulva lactuca</i> L.	<i>Cirrularia gmelini</i> (Grunow) Tokida et Masaki
<i>Ulva</i> sp.	<i>Clathromorphum circumscriptum</i> (Stroemf.) Fosl.
Order Schizogoniales	<i>Clathromorphum compactum</i> (Kjellm.) Fosl.
<i>Prasiola borealis</i> Reed	<i>Clathromorphum loculosum</i> (Kjellm.) Fosl.
<i>Rosenvingiella</i> sp.	<i>Clathromorphum nereostratum</i> Lebednik
Order Cladophorales	<i>Clathromorphum reclinatum</i> (Fosl.) Adey
<i>Chaetomorpha melagonium</i> (Weber et Mohr) Kütz.	<i>Constantinea rosa-marina</i> (Gmelin) P. et R.
<i>Cladophora</i> sp.	<i>Corallina pilulifera</i> P. et R.
<i>Lola lubrica</i> (S. et G.) A. et G. Hamel	<i>Corallina vancouveriensis</i> Yendo
<i>Spongomorpha spinescens</i> Kütz.	<i>Dumontia simplex</i> Cotton
Order Chlorococcales	<i>Endocladia muricata</i> (P. et R.) J. Ag.
<i>Codiolum petroceldis</i> Kuckuck	<i>Gloiopeltis furcata</i> (P. et R.) J. Ag.
Order Codiales	<i>Halymenia</i> sp.
<i>Codium ritteri</i> Setch. et Gardn.	<i>Hildenbrandia prototypus</i> Nardo
<i>Halicystis</i> sp.	<i>Lithophyllum</i> spp.
Phylum Phaeophycophyta	<i>Lithothamnium</i> spp.
Order Ectocarpales	<i>Mesophyllum aleuticum</i> Lebednik
<i>Ectocarpus tomentosus</i> (Hudson) Lyngb.	Order Gigartinales
<i>Pylaiella littoralis</i> (L.) Kjellman	<i>Ahnfeltia plicata</i> (Hudson) Fries
<i>Ralfsia fungiformis</i> (Gunnerus) Setch. et Gardn.	<i>Gigartina pacifica</i> (Kjellman) Tokida
Order Chordariales	<i>Iridaea cornucopiae</i> P. et R.
<i>Anelopus filiformis</i> (Harvey) Papenf.	<i>Petrocelis franciscana</i> S. et G.
<i>Anelopus japonicus</i> (Harv.) Wynne	<i>Petrocelis middendorffii</i> (Ruprecht) Kjellman
<i>Chordaria flagelliformis</i> (Müll.) C. Ag.	<i>Platoma</i> sp.
<i>Leathesia difformis</i> (L.) Areschoug	<i>Rhodoglossum pulchra</i> (Kützling) Setch. et Gardn.
Order Desmarestiales	<i>Turnerella</i> sp.
<i>Desmarestia intermedia</i> P. et R.	Order Rhodymeniales
Order Dictyosiphonales	<i>Halosaccion glandiforme</i> (Gmelin) Ruprecht
<i>Coilodesme bulligera</i> Stroemfelt	<i>Rhodymenia palmata</i> (L.) Greville
<i>Coilodesme fucicola</i> (Yendo) Nagai	Order Ceramiales
<i>Dictyosiphon foeniculaceus</i> (Hudson) Greville	<i>Amphisiphonia pacifica</i> Hollenberg
<i>Petalonia fascia</i> (Lyngb.) Link	<i>Antithamnion floccosum</i> (Müller) Kleen
<i>Scytosiphon lomentaria</i> (Lyngb.) Link	<i>Antithamnion shimamuranum</i> Nagai
<i>Soranthra ulvoidea</i> P. et R.	<i>Asterocolax hypophyllophila</i> Wynne
Order Laminariales	<i>Callithamnion californicum</i> Gardner
<i>Agarum cribrosum</i> Bory	<i>Callithamnion</i> sp.
<i>Alaria crispa</i> Kjellman	<i>Ceramium</i> sp.
<i>Alaria fistulosa</i> P. et R.	<i>Heterosiphonia</i> sp.
<i>Alaria praelonga</i> Kjellman	<i>Hymenena ruthenica</i> (P. et R.) Zinova
<i>Alaria pylaii</i> (Bory) Greville	<i>Hypophyllum dentatum</i> Wynne
<i>Cymathere triplicata</i> (P. et R.) J. Ag.	<i>Hypophyllum ruprechtianum</i> Zinova
<i>Fucus distichus</i> L.	<i>Laingia aleutica</i> Wynne
<i>Hedophyllum sessile</i> (C. Ag.) Setch.	<i>Membranoptera serrata</i> (P. et R.) Zinova
<i>Laminaria dentigera</i> Kjellman	<i>Membranoptera setchellii</i> Gardner
<i>Laminaria groenlandica</i> Rosenvinge	<i>Membranoptera spinulosa</i> (Rupr.) Zinova
<i>Laminaria longipes</i> Bory	<i>Microcladia borealis</i> Ruprecht
<i>Laminaria yezoensis</i> Miyabe	<i>Myriogramme kjellmanianum</i> Zinova
<i>Nereocystis luetkeana</i> (Mert.) P. et R.*	<i>Nienburgia prolifera</i> Wynne
<i>Thalassiosiphon clathrus</i> (Gmelin) P. et R.	<i>Odonthalia floccosa</i> (Esper) Falkenberg
Phylum Rhodophycophyta	<i>Pantoneura juergensii</i> (J. Ag.) Kylin
Order Bangiales	<i>Phycodrys amchitkensis</i> Wynne
<i>Bangia fuscopurpurea</i> (Dillw.) Lyngb.	<i>Phycodrys riggsii</i> (Gardner)
<i>Porphyra amplissima</i> (Kjellman) Setchell et Hus	<i>Platythamnion</i> sp.
<i>Porphyra ochotensis</i> Nagai	<i>Polysiphonia pacifica</i> Hollenberg
<i>Porphyra perforata</i> J. Ag.	<i>Polysiphonia</i> sp.
<i>Porphyra pseudolinearis</i> Ueda	<i>Pterosiphonia gardneri</i> Hollenberg
<i>Porphyra purpurea</i> (Roth) C. Ag.	<i>Pterosiphonia</i> sp.
<i>Porphyra tasa</i> (Yendo) Ueda	<i>Ptilota asplenoides</i> (Esper) C. Ag.
<i>Porphyra umbilicalis</i> (L.) J. Ag.	<i>Ptilota filicina</i> (Farlow) J. Ag.
<i>Porphyra variegata</i> (Kjellman) Hus	<i>Tokidodendron bullata</i> (Gardner) Wynne
<i>Porphyra yezoensis</i> Ueda	<i>Yendonia crassifolia</i> (Rupr.) Kylin
<i>Porphyrella gardneri</i> Smith et Hollenb.	<i>Zinovaea acanthocarpa</i> Wynne

*This species was found only in drift on beaches and was never found attached to rocks in the Amchitka coastal area.

Fig. 2—Schematic diagram of topographic features and biological regions of a typical intertidal bench.

Figure 4 shows schematically the relationship of wave action (exposure*) to the bench configuration. At low tide wave fronts (1) approaching the bench break solely along the seaward face of the rampart (2). As the sea level rises, water flows over the rampart onto the benchflat (3), resulting in currents shoreward across the benchflat and in the channels. Approaching the moat (4), these currents turn and run parallel to the shore, finally emptying into sand troughs on either side of the bench (5). At high tide waves plunge over the then submerged rampart and dissipate most of their energy there. Ordinarily, only unidirectional flow occurs over the benchflat at high tide, and in some localities the moat area appears to be a river of seawater. Only during storms do waves reach and break on the beach or on the cliff itself. Even under these conditions there is little or no plunging action over the benchflat because of the uniformity of water depth. Of all the components of the rock bench, the rampart has the greatest exposure. Tidal phenomena are discussed elsewhere in this book. According to the tide tables, the tides alternate from diurnal in the spring phase to mixed semidiurnal in the neap phase, and the maximum tidal range is just over 2 m (O'Clair, Chap. 18, this volume). The lowest tides occur in June at about 1100 (BST) and in December at about 0100

(National Ocean Survey, 1971). Weinmann (1969) indicated that the low tide on any day may be about 1 hr later than predicted. During our studies at fixed points in the intertidal area, we found that the lowest tide within a spring tide cycle often occurred about 1 to 3 days later than predicted. There are also large irregular deviations from the

Fig. 3—View of the moat area of an intertidal bench at Duck Cove (IA-1) on Aug. 26, 1973.

*The term exposure as used in this chapter refers to exposure to wave action.

Fig. 4—Schematic diagram of wave exposure in relation to an intertidal bench. (See text for explanation of diagram.) [From P. A. Lebednik, F. C. Weinmann, and R. E. Norris, *BioScience*, 21: 657(1971).]

predicted tides from day to day. We have seen areas completely covered with seawater throughout one day, and the next day they would be uncovered even though the predicted tide heights were identical and there was little wave action. Nearshore currents are generally gentle except at Bird Cape and East Cape.

Armstrong (1971; Chap. 4, this volume) describes the island's climate in detail. We consider here those factors of particular importance to littoral algae. Record high and low temperatures recorded at Amchitka during 1943 through 1948 were $+18.3^{\circ}\text{C}$ and -10.0°C , whereas extreme mean daily high and low temperatures were $+10.6^{\circ}\text{C}$ and -2.2°C , respectively. Perhaps most critical to littoral algae is the occasional coincidence of low tides with temperature extremes. In the comparison of maximum and minimum mean daily temperatures at various times of the year with times of predicted low tides, two such periods appear possible: an air temperature of about $+9^{\circ}\text{C}$ near noon in August coinciding with water at the -61-cm (-2.0-ft) level and an air temperature of -0.3°C near midnight in January above water at the -39.6-cm (-1.3-ft) level. The former is about equivalent to seawater temperatures at that season and would not appear to be critical, but the latter extreme, besides being more than 4° below ambient sea temperatures, is below the freezing point and may represent a critical stress factor for littoral organisms. Indeed, we have seen ice forming on emersed seaweed and surface freezing of pools during nighttime winter low tides.

Desiccation as well as temperature stress may occur in summer months when low tides coincide with clear skies and calm seas. Since clear skies and calm seas are rare at Amchitka (Burgner et al., 1969; Armstrong, 1971; Chap. 4, this volume), these conditions occur infrequently.

Wave exposure depends on local winds and the incoming swell from distant sources. The lowest

mean monthly wind speed of 13.8 knots occurs in July. Wind speeds and durations significantly greater than this occur in the fall, blowing from the southwest sector (Armstrong, 1971; Chap. 4, this volume). The Pacific Ocean coast receives swells of a greater wavelength than the Bering Sea coast owing to the greater fetch in that direction, but no data on swell frequency are available. The Bering Sea coast has smaller swells than the Pacific Ocean coast, and heavy wave action is less often observed. In the evaluation of the degree of exposure, caution must be exercised because bench topography strongly influences exposure of the intertidal area.

Seawater conditions are of great importance to sublittoral communities. In the surrounding off-shore surface waters, winter conditions are about 3°C temperature and 33 ‰ (parts per thousand) salinity (McAlister, 1971; McAlister and Favorite, Chap. 16, this volume); in summer they are about 6°C temperature and 30 ‰ salinity (Burgner et al., 1968). There is no sharp thermocline at any season above 30-m (100-ft) depth, the limit of our collecting activities. In numerous profiles taken in August 1967, neither salinity nor temperature changed more than one unit from the surface to 114-m (374-ft) depth (Burgner et al., 1968). At the shore seawater temperatures ranged from a minimum of 2°C in winter to a maximum of about 8°C on the Bering Sea coast and 10°C on the Pacific Ocean coast in summer. Thus the annual range of temperature is only 8°C at maximum.

Turbidity of water is an important limiting factor in the determination of the maximum depth of sublittoral algal communities. Although no measurements are available, it can be said that the water surrounding Amchitka Island is one of the least turbid waters in high northern latitudes. It is probably nearly comparable to the extremely clear waters reported for tropical areas. The best indication of water clarity is the depth distribution of the algal communities themselves.

The composition of offshore bottom substrates varies widely around Amchitka. Sand, ledge, gravel, and cobble bottoms, in approximate order of frequency, may be found on either side of the island. In all cases, down to depths reached by scuba diving [about 30 m (100 ft)], these substrates are clean of fine detrital deposits. No true mud bottoms were observed in numerous dives around the island.

LITTORAL ZONATION

Along rocky coastlines the distribution of marine organisms uncovered at low tide is extremely complex and depends on many factors

(Lewis, 1964). A major factor influencing distribution, aside from the tidal regime, is the degree of exposure (opposite of protected or sheltered). In highly exposed areas on the open coast, so-called intertidal marine organisms may extend well above the theoretical upper limits of the tides, indicating that the distribution of these organisms cannot be defined by a single physical factor, such as tidal levels. However, the extensive literature on this subject (see Lewis, 1964, for a review of the literature) indicates that marine organisms on most rocky coastlines of the world are observed in zones or belts ("... horizontally extensive, biotically distinct..." groupings of organisms, Doty, 1957) that are arranged one above the other in a pattern of zonation. Many systems of terminology have been used to describe and classify the zonation of rocky shores. It is generally agreed that the organisms themselves best define the zones, and in this chapter we have adopted the schemes of Stephenson and Stephenson (1949) and Lewis (1964) with slight modification (see Table 3). The

The boundary between the supralittoral fringe and midlittoral areas is usually defined at the upper limit of barnacles (Stephenson and Stephenson, 1949). Because barnacles are rare at Amchitka and do not form a distinct zone there, we have assigned the boundary between these two areas to the upper limit of *Fucus distichus*. In this chapter no attempt is made to formally subdivide the sublittoral region. For convenience, the portion of the sublittoral region exposed by the lowest tides is referred to as the sublittoral fringe (infralittoral fringe of Stephenson and Stephenson, 1949). In the supralittoral fringe and midlittoral areas, zones of limited vertical extent, each usually dominated by a single species, are observed in a consistent vertical sequence (zonation) over large horizontal distances of coastline. In the midlittoral area, where the greatest number of littoral species and the most complex zonation occur, a further breakdown of zones into *associations* is possible. In this chapter an association refers to an area that is locally dominated by a single species but does not

Table 3—Classification Scheme and Approximate Elevations Above Mean Lower Low Water of the Littoral Vegetation of Amchitka Island*

Region	Area	Zone	Association	Elevation, cm
Littoral	Supralittoral fringe	<i>Prasiola</i>		185 to 230
		<i>Rhodochorton</i>		125 to 190
		<i>Porphyra-Ulothrix</i>		75 to 140
	Midlittoral	<i>Fucus</i>		10 to 80
		<i>Hedophyllum</i>	<i>Ulva</i>	0 to 15
			<i>Analiplus</i>	
			<i>Corallina</i>	
			<i>Halosaccion</i>	
Sublittoral	Sublittoral fringe	<i>Alaria</i>		5 to 15
		<i>Laminaria</i>		0 to -300

*Modified from Weinmann (1969).

littoral region (littoral zone of Lewis) extends from the upper limit of the lichen (*Verrucaria*) zone down to the upper limit of *Laminaria* (*L. longipes* at Amchitka). The sublittoral region (sublittoral zone of Lewis) has as its upper limit the top of the *Laminaria* population, and its lower limit for the algae is defined as the greatest depth at which benthic algae occur. The littoral region is usually divided into an upper supralittoral fringe area (Stephenson and Stephenson, 1949; littoral fringe of Lewis, 1964) and a lower midlittoral area (midlittoral zone of Stephenson and Stephenson, 1949; eulittoral zone of Lewis, 1964).

necessarily have horizontal contiguity. Thus, within the *Hedophyllum* zone one can recognize several associations (including the *Hedophyllum* association), each of which is named according to the dominant alga.

It is generally agreed that the application of these terms is often arbitrary and that the implication of discrete zones and associations will not hold up to close examination of littoral communities. Despite these drawbacks, apparently no better system is available at present with which one can compare the general features of littoral zonation of a particular locality with those of another area.

The classification of zones and associations as used in this chapter is intended solely as a general framework that we hope will enable the reader to visualize the major features of the marine vegetation at Amchitka.

Methods

Weinmann's objective was to make an initial description of algal distribution in the littoral region (Weinmann, 1969). In March and April 1968, he established one transect at Makarius Bay on the Pacific Ocean coast (T-1) and another at Square Bay on the Bering Sea coast (T-2). Species distributions in the supralittoral fringe were recorded by visual observation and in the midlittoral area and the sublittoral fringe by the removal of adjacent 90- by 20-cm samples of algae along the entire transect line. The abundance of each species was measured by dry-weight analysis of each sample. The abundance of crustose coralline algae was estimated in percent cover values. Associations were studied by placing 35- by 35-cm or 20- by 20-cm quadrats in the vicinity of the transect (but not within the dry-weight samples) and estimating the percent cover with the use of the Braun-Blanquet method (den Hartog, 1959).

The transects established by Weinmann were easily accessible yet sufficiently distant from the planned nuclear test that it was thought possible to use them for two further purposes: (1) To study the seasonal changes in littoral species and (2) as controls for any test effects that might be detected in other areas. For these studies the sample areas could not be disturbed; so a photographic sampling frame (Fig. 5) was designed to sample a 0.25-m² quadrat by means of an underwater camera accompanied by a strobe. A photograph and notes for each plot were taken in the field. In the laboratory the 6- by 6-cm color transparencies were viewed with a hand magnifier over a light box with a clear plastic grid, and the percent cover of each species was determined quantitatively. Since it was necessary that the plants remain undisturbed, the composition and percent cover of the understory vegetation could not be determined with this technique.

The plots were originally located by measuring distances from a base-line point, but later, because of the problems in measuring, each plot was marked by nailing polypropylene rope flags into the soft breccia bedrock.

In an attempt to correlate the photographic sampling method with dry-weight values, a third transect (T-3) at Rifle Range Point was sampled in May 1969 with the use of both methods. This transect, which was studied by Lebednik, was not

resampled. The sampling dates of all marine algal studies are given in Table 1.

Description of Algal Zones and Associations

The zonation and floristic composition of the littoral region were studied by Weinmann (1969) at Makarius Bay on the Pacific Ocean coast and Square Bay on the Bering Sea coast. The following description is based on his study.

Seven zones, each denoted by the dominant species in it, have been characterized at Amchitka (Table 3). In areas at Amchitka with steep slopes, the general vertical relationship holds, but flat topography tends to blur the distinction between adjacent zones. Horizontally, the upper three zones are discontinuous, depending on the presence of suitable substrate and exposure conditions. Some of these zones are present only at certain seasons of the year.

Only qualitative data were obtained in the supralittoral fringe area. Inconspicuous, but sometimes occupying large areas, each zone of the

Fig. 5—Photographic sampling apparatus used for quantitative intertidal studies.

supralittoral fringe consists of a very few species adapted to the stress conditions of the high littoral environment. Thus only one association can be recognized in each of these zones.

The highest zone is characterized by the macroscopic alga *Prasiola borealis*, a species found throughout the cold waters of the North Pacific. It occurs on the tops of large boulders, the sides of sea stacks, and on high areas of the rampart on rock benches. A luxuriant green carpet of this species may be conspicuous on promontories where sea birds alight and provide a habitat rich in nutrients. In places maritime lichens and small nearly invisible blue-green algae may occur with this species.

Rhodochorton purpureum, the species characterizing the next lower zone, occurs only in shaded or semishaded areas. This habitat preference limits its distribution to sea cliffs that are exposed at least intermittently to salt spray. Typically, this species can be found in caves or below overhanging rock on vertical faces, such as at Rifle Range Point, but occasionally it may be found in the open, especially where suitable conditions occur with a north or east aspect. The vertical distribution of the species begins about 40 cm (16 in.) above, and may extend to as much as 340 cm (134 in.) above, the highest local *Fucus distichus* plants. An undetermined species of *Cladophora* sometimes occupies as much as 25% of the area in the *Rhodochorton* zone, and *Ulothrix flacca* occurs sparsely in the lower portion of the zone. This zone seems to occur more frequently along the Bering Sea coastline than on the Pacific Ocean coastline, a fact that may be attributed to the north aspect or to the less-well-developed benches and consequent increase in exposure on that side of the island.

Immediately below the *Rhodochorton* zone in elevation but much more widespread is the *Porphyra-Ulothrix* zone. Species of these genera are dominant components of the vegetation on the boulder shores that are common on the Bering Sea coast (Fig. 6) as well as at high cliff, stack, and rampart locations. *Bangia fuscopurpurea* occurs sporadically in this zone. The *Porphyra* species usually have their lower limit somewhat above the *Fucus* zone, leaving a band sparsely occupied by *Ulothrix flacca*. All but one of the *Porphyra* species (probably *P. pseudolinearis*) occur only in this zone. *P. pseudolinearis*, a species that attains lengths of 50 to 80 cm (20 to 31 in.), is commonly found on cobbles in the moat area of rock benches as well as in the upper portion of the *Fucus* zone.

The upper limit of the midlittoral region is defined as the upper limit at which *Fucus distichus* is found. At Amchitka its preferred habitat is on

the top of boulders in the beach or moat areas and in the lower zones on harder portions of the rock that project from the benchflat (Fig. 7). The *Fucus* zone occupies a vertical range of about 70 cm (28 in.). There are distinctly more species recorded in this zone than in the *Porphyra-Ulothrix* zone next above it (Fig. 8). *Pylaiella littoralis*, an epiphyte, is commonly found on mature *F. distichus* plants around the island. As Table 4 indicates, several species that occur in and characterize associations at lower levels also occur within the *Fucus* zone, but they rarely form associations at this level. Only *Iridaea cornucopiae*, *Ulva lactuca*, and *Gigartina pacifica* occur with a percent constancy greater than 50%.

The second zone-characterizing canopy species of the midlittoral region is *Hedophyllum sessile*. This is the major zone occurring on the benchflat area. *H. sessile* does not appear to be adapted to exposed conditions. Its preferred habitat is on the very flat benches at the appropriate level where it may reach biomass values of 12.2 kg/m² wet weight. On benchflats with a rolling topography, it occurs in depressions with little standing water (Fig. 9). The Amchitka plants have blades that lack bullation, but they have a large, continuous, more or less bowl-shaped morphology. In exposed areas, especially on the Bering Sea coast and on vertical ledges, there may be no *Hedophyllum* between the *Fucus* and the lower lying *Alaria* or *Laminaria* zones. In these situations the understory associations are conspicuous. The *Hedophyllum* zone has the greatest number of species of all the intertidal zones (Fig. 8).

Six associations can be recognized within the *Hedophyllum* zone (Table 4): *Ulva*, *Analipus*, *Corallina*, *Halosaccion*, *Hedophyllum*, and *Iridaea*.

Fig. 6—*Porphyra-Ulothrix* zone on the Bering Sea coast, July 20, 1971.

Fig. 7—Species composition and percent cover at the T-3 transect.

Fig. 8—Number of algal species (excluding blue-green and unicellular species) reported within the major algal zones at Amchitka.

Fig. 9—Shoreward *Hedophyllum* zone in Makarius Bay. Plot 2 of the T-1 transect is located on top of the boulder in the rear.

The *Analipus* association usually occurs on boulders just below the *Fucus* zone and never extends out far along the benchflat. Most of the year it is recognizable only as an extensive holdfast system, but in May the upright fertile fronds make this species more noticeable (Wynne, 1971). *Ulva lactuca*, *Iridaea cornucopiae*, and *Halosaccion glandiforme* are commonly associated species.

Corallina pilulifera commonly occurs over the benchflat from below the *Fucus* zone to the outer

portion of the benchflat but forms an association (together with *Clathromorphum loculosum* and *C. circumscriptum*) only on extremely flat areas on the bench. Except for *Clathromorphum loculosum* and *C. circumscriptum*, only *Halosaccion glandiforme* occurs in this association with a percent constancy greater than 50%.

Halosaccion glandiforme is one of the most conspicuous of the association-characterizing species. It occurs in all the associations of the

Table 4—Percent Constancy Values of Algal Species in Littoral Algal Zones and Associations of Amchitka*

Zone:	Fucus	Hedophyllum						Alaria	Laminaria
		Ulva	Analipus	Corallina pilulifera	Halosaccion glandiforme	Hedophyllum	Iridaea		
Association									
Species									
<i>Ahnfeltia plicata</i>		10						14	
<i>Alaria crispa</i>				20		10		100	8
<i>Analipus filiformis</i>	10		100		40		50		
<i>Bossiella cretacea</i>									8
<i>Coilodesme bulligera</i>		40							
<i>Corallina pilulifera</i>	30	10	11	100	50	100	20		
<i>Corallina vancouveriensis</i>								86	67
<i>Cladophora</i> sp.							10		
<i>Fucus distichus</i>	100		22		30		10		
<i>Gigartina pacifica</i>	60	10		20	30	10	20	28	
<i>Halosaccion glandiforme</i>	40	20	56	50	100	30	100	28	
<i>Halymenia</i>	10	20				40	10		
<i>Hedophyllum sessile</i>					20	100	40	14	
<i>Hildenbrandia</i>	20								
<i>Iridaea cornucopiae</i>	70	50	56	40	80	70	100	71	
<i>Laminaria longipes</i>				20		20		43	100
<i>Microcladia borealis</i>		20		10	40	20	20		
<i>Odonthalia floccosa</i>	10	50				20		43	
<i>Petrocelis middendorffii</i>	20		11		20		20	14	
<i>Ptilota asplenioides</i>									17
<i>Ptilota filicina</i>				10		20		43	50
<i>Ralfsia fungiformis</i>	20	10	22	10		20	10	43	
<i>Rhodomenia palmata</i>			11		40	10			
<i>Tokidadendron bullata</i>						20		14	8
<i>Ulva</i> sp.	50	100	89		60	30	50		
Encrusting corallines	30	40	11	60	20	80	30	86	100
Total No. species in each association		12	10	10	12	16	14		
Total No. species in each zone	13				22			14	8

*From Weinmann (1969).

midlittoral zones and has an average percent constancy of 53%. The most important of the associated genera are *Corallina*, *Iridaea*, and *Ulva*.

The *Hedophyllum* association has the greatest number of species (16) in it, but outside its association *H. sessile* occurs only in the *Halosaccion* and *Iridaea* associations of the *Hedophyllum* zone, and in no case does it occur with greater than 40% constancy. *Halosaccion glandiforme* is often associated with *Hedophyllum*, and encrusting coralline algae and *Iridaea* also occur frequently in this association. The *Hedophyllum* association occurs over a small vertical range (Weinmann, 1969), but, since this frequently coincides with the level of the benchflat, it covers extensive areas (Fig. 7).

Iridaea cornucopiae is the most frequent species throughout all the associations of the intertidal region (average percent constancy of 67%), and the

Iridaea association is second only to the *Hedophyllum* association in the number of species present in it (14). Since this species is dark or frequently black and since it grows low against the rock, *I. cornucopiae* is not nearly as conspicuous as *H. glandiforme*, yet it occurs with a greater abundance overall.

The *Ulva* association is found primarily in the upper part of the *Hedophyllum* zone. Weinmann (1969) found *U. lactuca* common during May through September in shallow tide pools just below the *Fucus* zone. Scattered plants of *U. lactuca* can be found in any part of the benchflat at most times of the year, but the species appears to be most abundant in the moat area (Burgner et al., 1969; 1971) (Figs. 3 and 7). The species most commonly found with *U. lactuca* in this association are *I. cornucopiae* and *Odonthalia floccosa*.

The Pacific coast intertidal benches of Amchitka demonstrate that some of these species, given appropriate conditions, can form nearly pure stands on particular benchflats. Figure 7 shows an abundance profile for a transect at Rifle Range Point indicating extensive dominance by *H. sessile*. *Corallina pilulifera* also sometimes occupies extensive benchflat areas nearly to the exclusion of all other algal species.

The presence of a distinct *Alaria* zone along the Bering Sea coast may be correlated with the lack of *Hedophyllum*. When *Alaria crispa* and *Hedophyllum sessile* occur together, *A. crispa* generally occupies the more seaward portion but may grade slowly into the *Hedophyllum* zone. The association analysis (Table 4) shows that *A. crispa* occurs in insignificant frequencies in other associations, but a high number of species (14) occur in association with it. *A. crispa* was not present on the Pacific coast transect in 1968 (Weinmann, 1969), but we found this species there from 1969 to our final visit in 1973.

On the outer face of the rampart, plants of various *Alaria* species form an association in the most exposed area of the bench (Fig. 10). Morphologically these plants differ from those of the benchflat in that they have tufts of thick linear sporophylls; from each tuft protrudes a short ragged main lamina, the whole being reminiscent of small *Postelsia palmaeformis* plants seen in similar habitats along the west coast of North America. These plants frequently have their upper limit above that of the *Fucus distichus* plants on the landward portion of the bench.

Fig. 10—Rampart area of an intertidal bench at Rifle Range Point dominated by *Alaria* sp.

The lowest zone of the intertidal area is that characterized by *Laminaria longipes*. This sublittoral fringe species occupies large areas of rock down to -3 or -5 m (-10 or -15 ft), thus constituting a transition species between the littoral and sublittoral regions. Most of the species associated with this zone are sublittoral species at the upper limit of their ranges, and the number of species found in this zone (8) is fewer than that in the three previous zones. Regardless of exposure or bench topography, *L. longipes* appears to be fairly consistent in occupying ledges from about mean lower low water downward. Unlike all the other canopy-forming kelps at Amchitka, which form a single stipe from a limited holdfast, *L. longipes* grows by means of a prostrate branching stipe that produces numerous upright stipes and blades (Markham, 1972).

Sublittoral fringe vegetation is found in channels (Fig. 1) cutting through the bench and in deep tide pools (which are rare) on the bench. In one sense much of the benchflat could be considered a tide pool since at low tide seawater stands up to a few centimeters deep in many undrained depressions. However, only littoral species are present in these shallow depressions. The rare deep tide pools have an abundance of *Thalassiophyllum clathrus*, *Ptilota* spp., *Cymathere triplicata*, and other sublittoral species in them. *L. longipes* is only occasionally seen in tide pools.

Tatwaki and Kobayashi (1934) recognized three associations (apparently comparable to our zones) in the littoral belt of the Aleutian Islands: (1) *Alaria-Hedophyllum-Laminaria*, (2) *Halosaccion glandiforme*, and (3) *Fucus evanescens*. The first association includes our *Laminaria longipes* and *Hedophyllum sessile* zones. The recognition of a separate *H. glandiforme* zone probably resulted from the fact that their observations were made only in the summer when this species is most conspicuous.

When the distributions of the major littoral species are plotted against distance on the benchflat perpendicular to the shoreline (Figs. 7 and 11), the distribution of the zones is not strictly correlated with elevation. This result is surprising because the primary control over the distribution of intertidal organisms is usually thought to be exerted by some tidal factor or factors (Doty, 1946). No biological interactions, such as herbivory, can account for the particular case at hand. Our explanation is that bench topography and offshore kelp beds modify wave action so that there is a gradient of exposure across the intertidal benches which gives an effect similar to that of protected versus exposed coastlines but on a much

Fig. 11—Schematic diagram of the major zones on the Square Bay transect (T-2).

smaller scale (Weinmann, 1969; Lebednik et al., 1971). This is perhaps the most unusual feature of the littoral flora at Amchitka.

Seasonal and Annual Variation

The only observations of seasonal variation of species in the supralittoral fringe are the comments of Weinmann (1969) that *Ulothrix flacca* and *Porphyra pseudolinearis* reached a peak of abundance in March and April. Only a few *Porphyra* plants could be seen in May, and by August–September the zone was nearly absent.

A preliminary account of seasonal variation in the midlittoral area was given by Lebednik et al. (1971). The following data are from a more complete study in which frequencies of the major species occurring in the midlittoral and sublittoral fringe areas from February 1972 to August 1973 were recorded. These data are shown in Tables 5 and 6.

As shown in the tables, the frequency of *Fucus distichus* changed little on the T-1 transect, but an increase was seen in late summer 1972 on T-2. Data from one plot of the T-2 transect show that cover values of *Fucus distichus* remained high throughout the year, but they had a tendency to peak in June–August. This is shown more graphically in tracings of *Fucus distichus* plants from photographs of a plot on the T-1 transect from February 1972 to August 1973 (Fig. 12). *Fucus* sporelings probably settled on the hard rock fragment (indicated by the dashed line in A) in the summer of 1971. During 1972 significant growth occurred, increasing the percent cover from 3.1% in February to 28.1% by October. Surprisingly, significant growth occurred during the winter so that by April 1973 cover had increased to 49.3%, although the growth in winter was certainly smaller than that in summer. Also, the receptacles (stippled in Fig. 12) were more conspicuous and more developed in late summer than in winter. The final value of 73.6% cover measured in August 1973

probably represented the maximum development of these plants.

At Amchitka *Hedophyllum sessile* develops very large entire blades without bullation or longitudinal splitting, and most plants persist from year to year. Widdowson (1965) concluded that bullation is primarily caused by exposure to sunlight and splitting is due to exposure. The lack of bullation or longitudinal splitting at Amchitka is consistent with his hypothesis. Clear skies are rarely present (see sky cover in Armstrong, Chap. 4, this volume), and *H. sessile* appears to be restricted to relatively protected localities on Amchitka. Colorless marginal zones were observed on *H. sessile* plants in February, becoming most evident in April of each year; presumably this represented the time of spore release in these plants. The frequency of *H. sessile* was constant at T-1 but started to increase in April 1973 on T-2. Overall, the abundance of *H. sessile* appeared to remain constant, but cover probably increased slightly owing to growth in summer.

Analipus spp. holdfasts are present year round, but upright fertile (spore-bearing) fronds are produced in May (Weinmann, 1969; Wynne, 1971). We believe that the apparent summer decrease in frequency of occurrence of this species, as shown in Tables 5 and 6, does not reflect an actual decrease in population but is due to the covering of plants by summer growth of canopy species.

Corallina pilulifera exhibited some late winter–early spring die-off on T-1 but none on T-2. Some of the variations in frequency of *C. pilulifera* were due to the occasional covering of some plants by nearby kelp fronds.

Halosaccion glandiforme and *Porphyra* spp. are annuals and show the most conspicuous seasonal changes in abundance of all littoral species. Nevertheless, frequencies of *H. glandiforme* were fairly constant at T-1 and T-2 (Tables 5 and 6). The percent cover values of *H. glandiforme* for five plots at T-2 are given in Fig. 13. This species showed a peak in cover in August and a minimum

Table 5—Frequency of Occurrence of Common Species in 18 0.25-m² Plots at T-1 from February 1972 Through August 1973

Species	Feb. 1972	April 1972	June 1972	Aug. 1972	Oct. 1972	Apr. 1973	Aug. 1973
<i>Alaria crispa</i>	6	7	7	6	6	9	6
<i>Analipus filiformis</i>	3	3		1		2	
<i>Clathromorphum circumscriptum</i>	1	2		1	1	1	1
<i>Corallina pilulifera</i> (live)	4	4	3	3	4	4	4
<i>Corallina pilulifera</i> (dead)	1	3	1			1	
<i>Fucus distichus</i>	4	5	4	5	5	5	5
<i>Halosaccion glandiforme</i>	5	5	5	5	5	5	5
<i>Hedophyllum sessile</i>	12	11	12	13	12	12	13
<i>Iridaea cornucopiae</i>	6	5	4	5	5	5	5
<i>Laminaria longipes</i>	4	4	3	3	5	5	5
<i>Ulva</i> sp.	3	4	3	2	5	5	3

Table 6—Frequency of Occurrence of Common Species in 24 0.24-m² Plots at T-2 from February 1972 Through August 1973

Species	Feb. 1972	April 1972	June 1972	Aug. 1972	Oct. 1972	Apr. 1973	Aug. 1973
<i>Alaria crispa</i>	10	11	9	10	11	16	15
<i>Analipus filiformis</i>	1	3				2	1
<i>Clathromorphum circumscriptum</i> (live)	7	6	7	3	8	6	6
<i>Clathromorphum circumscriptum</i> (dead)	2	4	3	3	5	1	1
<i>Corallina pilulifera</i> (live)	5	5	4	1	4	5	3
<i>Fucus distichus</i>	3	4	5	7	7	6	6
<i>Halosaccion glandiforme</i>	4	8	7	7	8	7	7
<i>Hedophyllum sessile</i>	3	2	3	4	3	5	6
<i>Iridaea cornucopiae</i>	9	9	8	8	8	8	8
<i>Laminaria longipes</i>	7	6	6*	6	7	6	4
<i>Ulva</i> sp.	7	6	4	8	7	9	8

*Dead plants were found with a frequency of 4 in this sample.

in winter, probably February–March. In agreement with Weinmann (1969), we observed that the increase in cover was due to the growth of new upright thalli in early summer, although a few plants survived for two summers.

Iridaea cornucopiae has a perennial crustose base that produces upright blades each year in early spring. The frequency of this species (Tables 5 and 6) was remarkably constant throughout the year. Figure 14 shows that the cover of the species (based on the upright blades because the crusts are impossible to distinguish in the photographs) peaked in early summer and declined thereafter as the blades became fertile and disintegrated in the process of releasing spores.

Ulva lactuca showed a great deal of irregularity in its frequency of occurrence. This is a species characteristic of the moat area of the benchflat, an area of annual deposition and removal of silt. This factor contributes to a strong seasonal variation in cover.

Another species common in moat areas, *Clathromorphum circumscriptum*, also shows a

great deal of variability in frequency of occurrence. This species is a slow-growing crustose coralline alga, and seasonal variability in cover would not be expected. However, the percent cover on four plots at T-2 showed definite seasonal variation and die-off (Fig. 15). This undoubtedly resulted from the removal of silt by storms and uncovering of plants in winter and buildup of silt and burying of plants in summer. As shown by the peak in dead cover in Fig. 18, some summer mortality occurred in the population, but some plants survived and continued growing the following winter.

Alaria crispa sporelings appear in the spring, and growth continues throughout the summer. A slight increase in frequency was seen in the spring of 1972. An even greater increase in frequency was recorded in the spring of 1973, when *A. crispa* was also exceptionally abundant in other midlittoral areas we visited. This was the only instance we recognized of a definite annual variation in this species' abundance at Amchitka. Because *Alaria* plants are strap-shaped, attached at one end and usually much larger than a 0.25-m² quadrat,

Fig. 12—Growth and reproduction of *Fucus distichus* plants on plot 7 of the T-1 (Makarius Bay) transect. A, Feb. 22, 1972; B, Apr. 15, 1972; C, June 10, 1972; D, Aug. 20, 1972; E, Oct. 22, 1972; F, Apr. 5, 1973; G, Aug. 25, 1973. Stippled portions are receptacles; the dashed line in "A" indicates the outline of a hard volcanic rock fragment on which the plants were growing.

Fig. 13—Percent cover of *Halosaccion glandiforme* on the T-2 transect from October 1971 to August 1973. ●, plot 3. ×, plot 4. ○, plot 8. □, plot 9. △, plot 11. Species cover too small to measure accurately is assigned a value of 0.1%.

Fig. 14—Percent cover of *Iridaea cornucopiae* on plot 3, T-1 transect, from February 1972 to August 1973.

Fig. 15—Percent cover of live and dead *Clathromorphum circumscriptum* on the T-2 transect from October 1971 to August 1973. ●, plot 2. ×, plot 3. ○, plot 4. □, plot 9. Species cover too small to measure accurately is assigned a value of 0.1%.

abundance data from the transects are poor measures of growth and recruitment.

Generally *Laminaria longipes* exhibits no seasonal change in its populations. There were occasional dead patches, sometimes over a meter in diameter, within otherwise healthy areas of the species (Fig. 16). This phenomenon caused a decline in frequency on T-2 as seen in 1973, although visual observations indicated that in the zone as a whole die-off was more extensive in June 1972 (J. Isakson, personal communication). The

Fig. 16—Dead patches of *Laminaria longipes* at Duck Cove near IA-1, Aug. 26, 1973 (meter stick in one patch).

Fig. 17—Reproductive *Laminaria longipes* on plot 22 of the T-2 transect, April 1972. The photograph is of a 0.5- by 0.5-m ($1\frac{1}{2}$ - by $1\frac{1}{2}$ -ft) area. Reproductive areas that have released spores are conspicuous as white margins on blades.

release of zoospores results in marginal linear colorless patches on the fronds (Fig. 17), which are most conspicuous in April each year. This reproductive process is apparently not related to the mortality mentioned because in the later case

holdfasts, stipes, and meristematic areas degenerate and the blades are lost completely.

Comparison with Other Regions

There are many inherent problems in the comparison of studies of zonation from different parts of the North Pacific Ocean with our studies at Amchitka. Aside from any real differences that may exist, different application of vegetation terms may be found in different countries and even between workers within one country. Misidentification of species or other taxonomic problems may strongly influence the apparent similarities or differences between two studies (particularly in the older literature where recent taxonomic changes might make comparison with present species names very misleading). Finally, one must ask how representative of an entire geographic region a particular study is. These problems can be reduced somewhat by concentrating on species that are conspicuously and consistently dominant either as a zone or as an association, are easily identified, and/or are known to be characteristic of particular environmental conditions.

Kardakova-Prezhentsova (1938) made a detailed study of the littoral region of the Commander Islands. She found a zonation pattern very similar, if not identical, to that at Amchitka. The supralittoral zone was characterized by *Urospora penicilliformis*, *Bangia fuscopurpurea*, *Porphyra* sp. (all winter species), and *Prasiola borealis*. The principal species of the upper littoral zone (comparable to the midlittoral *Fucus* zone at Amchitka) were *Fucus distichus* (as *F. evanescens**), *Gloiopeltis furcata*, *Monostroma grevillei*, and *Anelopus japonicus*†. The occurrence in this zone of *Chordaria flagelliformis*, an arctic species, suggests a slightly colder environment than at Amchitka. The medium littoral zone of Kardakova-Prezhentsova is equivalent to both the *Hedophyllum* and *Alaria* zones at Amchitka. This difference probably reflects a matter of opinion rather than a significant difference in zonation because *Alaria* is seasonal and does not form a zone everywhere at Amchitka. The major species of the medium littoral zone at the Commander Islands were *Alaria lanceolata*, *Hedophyllum sessile* [as *H. subsessile*, see Widdowson (1965)], *Rhodomela larix*, and *Fucus distichus*. The lower littoral zone at the Commander Islands (comparable to the sublittoral fringe *Laminaria* zone at Amchitka) was dominated by *Laminaria longipes*, *L. dentigera*, *Thalassiohyllum*

**Fucus evanescens* is now recognized as a subspecies of *F. distichus* (Powell, 1957).

†For synonyms used in the literature (*Chordaria abietina* and *Heterochordaria abietina*), see Wynne (1971).

clathrus, *Codium adherens* (probably *Codium ritteri*), and *Pterosiphonia bipinnata*. Except for the absence of the *Halosaccion glandiforme* and *Iridaea cornucopiae* associations, the preceding description of zonation at the Commander Islands agrees very well with the results of our studies at Amchitka.

Spasskiĭ (1961) reported on the littoral zonation of southeastern Kamchatka. In the supralittoral region, two "horizons" were distinguished: (1) An upper first horizon of *Rhodochorton purpureum* and *Bangia fuscopurpurea* and (2) a lower second horizon of *Rhizoclonium riparium*. These horizons are probably comparable to the *Rhodochorton* and *Porphyra-Ulothrix* zones, respectively, of the supralittoral fringe at Amchitka. Spasskiĭ recognized three horizons in the littoral region which were, from top to bottom: (1) *Gloiopeltis coliformis*, (2) *Analipus japonicus*, *Chordaria flagelliformis*, and (3) *Corallina* and various Rhodophyceae and Laminariales. *Fucus distichus*, *Porphyra perforata*, *Ulva lactuca*, *Laminaria longipes*, and three species of *Alaria* were also present in the littoral region but were apparently not sufficiently abundant to establish zones or associations. The geographical distribution of *Hedophyllum sessile* does not extend beyond the Commander Islands (Kardakova-Prezhentsova, 1938; Widdowson, 1965).

The littoral zonation of the Kurile Islands was studied by Nagai (1940; 1941). In the northern Kurile Islands, he recognized a cold-water flora that he named the "upper boreal district." Within this district three formations were recognized in the littoral vegetation: (1) An upper *Fucus distichus* formation (including *Halosaccion saccatum*, *Ulva fenestrata*, *Porphyra* spp., *Iridaea cornucopiae*, *Ulothrix pseudoflaccida*, *Analipus japonicus*, and *Corallina pilulifera*), (2) a lower *Alaria angustata* formation, and (3) a *Laminaria longipes* formation. Thus it would appear that the zonation of littoral algae in the Kurile Islands is more similar to that of the Commander and Aleutian Islands than that of the southeastern coast of Kamchatka. Only the midlittoral *Hedophyllum* zone was not observed in the Kurile Islands.

Considerably less affinity in littoral zonation is seen on the east coast of Hokkaido. The main "belts" recognized by Taniguti (1962) were, from top to bottom: *Porphyra pseudocrassa*, *Pelvetia wrightii*, *Fucus distichus*, and *Laminaria longipedalis*. In exposed localities *Pelvetia* and *Fucus* were replaced by *Analipus japonicus* and *Iridaea cornucopiae* (as *Iridophycus*). *Corallina pilulifera* was also present. The presence of a distinctly southern element, *Sargassum*, signals a transition to a warmer water flora elsewhere on Hokkaido.

The littoral zonation of Sakhalin Island in the Okhotsk Sea was recently studied by Vozzhinskaya (1964b). On the southern coasts of the island, the supralittoral area was dominated by *Gloiopeltis capillaris*, which was often associated with *Porphyra* sp. and *Urospora* sp. The littoral region was characterized by three horizons (comparable to the midlittoral zones of Amchitka), which were, from top to bottom: (1) *Analipus japonicus*, (2) *Corallina pilulifera* and *Iridaea cornucopiae* (*Fucus* in protected localities), and (3) *Chordaria magellanica* and *Laminaria japonica*. The occurrence of *Sargassum* on the southern coasts once again indicates a transition to a warmer water flora.

From the comparison of the above studies with our study of Amchitka, one can conclude that the littoral zonation of the Commander Islands is nearly identical with that of Amchitka. The vegetation of the Kurile Islands is generally similar, but that of southeastern Kamchatka is less similar. Finally, the islands of Hokkaido and Sakhalin bridge the transition to a distinctly warmer water flora.

Practically no studies have been made of littoral zonation in the northern Bering Sea, which precludes a review of the arctic affinities of the Amchitka flora.

Along the west coast of North America, surprisingly few descriptive studies of littoral zonation have been done. Rigg and Miller (1949) reported on studies of littoral zonation at Neah Bay, on the Strait of Juan de Fuca. They distinguished seven zones in the littoral region, which were, from top to bottom: (1) *Ralfsia-Prasiola*, (2) *Endocladia-Gigartina*, (3) *Postelsia*, (4) *Halosaccion glandiforme*, (5) *Alaria*, (6) *Lessoniopsis*, and (7) *Laminaria andersonii*. The first zone occurred in their "splash zone" (comparable to the supralittoral fringe area of Amchitka). The second zone straddled the splash zone and the "upper intertidal zone," the latter including zones 3 and 4 (comparable to the *Fucus* and *Hedophyllum* zones of Amchitka). The "lower intertidal zone" of Rigg and Miller included zones 5 and 6, and zone 7 was classified the "demersal zone." Zones 6 and 7 appear to be comparable to the *Laminaria longipes* zone at Amchitka. Both *Fucus distichus* and *Hedophyllum sessile* occurred in abundance in the more protected areas studied by Rigg and Miller.

The above review indicates the variation of classification schemes as used by different workers in various parts of the North Pacific Ocean. The presence or absence of the large kelp species in the midlittoral area appears to have the greatest influence on littoral zonation schemes adopted by various authors. In contrast, the supralittoral fringe area can be recognized in most localities by the

presence of characteristic genera (*Prasiola*, *Porphyra*, *Ulothrix*, and *Bangia*) of wide geographical distribution and with a strong seasonal difference in abundance. The sublittoral fringe area is characterized in exposed localities by a dominance of kelps with massive holdfasts and strap-shaped blades.

According to some authors (Taniguti, 1962; Vozzhinskaya, 1964b) *Fucus* occurs in abundance only in relatively protected areas. The same distribution appears to characterize *Hedophyllum sessile* (Rigg and Miller, 1949). The morphology of *Hedophyllum* plants at Amchitka (smooth entire blades) also indicates a relatively protected environment (see Widdowson, 1965). These facts correlate with the idea presented above that the rock-bench topography provides an exposure gradient so that zonation of an exposed type is observed on the promontories and outer bench areas, whereas a more protected zonation pattern, including extensive *Hedophyllum* and *Fucus* zones and a diverse flora, characterizes the benchflat area.

these factors and to aid in predicting the effects of nuclear testing on littoral algal communities. In these experiments either the entire community or the canopy only was removed from permanently marked plots, and the subsequent colonization was recorded.

Methods

So that differences in colonization due to exposure could be accounted for, plots were established at sheltered (Makarius Bay), intermediate (Duck Cove), and exposed (Rifle Range Pt.) areas. These plots were completely independent of the T-1, T-2, and T-3 transects. Local differences in colonization in the midlittoral area were studied by establishing plots in pure stands (associations) of the following species: *Alaria crispa*, *Hedophyllum sessile*, *Corallina vancouveriensis*, and *Halosaccion glandiforme*. In the sublittoral fringe area, plots were established in the *Laminaria longipes* association. Not all associations were sampled at each locality (see Table 7). Sea-

Table 7—Summarized Descriptions of Plots Established for Denudation and Canopy-Removal Studies at Amchitka from March 1971 to April 1973

Species	Number of plots	Zone	Location	Manipulation
<i>Laminaria longipes</i>	22*	<i>Laminaria</i>	Makarius Bay	Rock denuded
<i>Laminaria longipes</i>	16*	<i>Laminaria</i>	Makarius Bay	Canopy removal
<i>Hedophyllum sessile</i>	18*	<i>Hedophyllum</i>	Makarius Bay	Rock denuded
<i>Halosaccion glandiforme</i>	16†	<i>Hedophyllum</i>	Makarius Bay	Rock denuded
<i>Corallina vancouveriensis</i>	14†	<i>Alaria</i>	Rifle Range Point	Rock denuded
<i>Alaria crispa</i>	18*	<i>Alaria</i>	Duck Cove	Rock denuded
<i>Alaria crispa</i>	12*	<i>Alaria</i>	Duck Cove	Canopy removal
<i>Hedophyllum sessile</i>	16*	<i>Hedophyllum</i>	Duck Cove	Canopy removal
<i>Hedophyllum sessile</i>	4*	<i>Hedophyllum</i>	Makarius Bay	Canopy removal
<i>Corallina vancouveriensis</i>	18†	<i>Alaria</i>	Duck Cove	Rock denuded

*1-m² plots (1 by 1 m).

†0.25-m² plots (0.5 by 0.5 m).

COLONIZATION STUDIES

Denudation experiments and studies of subsequent colonization have been suggested as a means of understanding the factors influencing the zonation of littoral algae (Chapman, 1943). Such studies have been conducted in Hawaii (Neal, 1930), California (Northcraft, 1948), Washington (Dayton, 1971), England (Kitching, 1937; Rees, 1940), South Africa (Bokenham, 1938), and elsewhere. No such experiments had been performed in the Aleutian Islands prior to our studies. Starting in 1971 Palmisano (1975) conducted denudation experiments at Amchitka to delineate

seasonal differences were studied by clearing plots in some areas at nearly bimonthly intervals from March 1971 to December 1972 and in April 1973 (see Table 1). Two types of manipulation (each on separate plots) were used: (1) Total denudation of rock surface by the removal of all organisms and (2) removal of the canopy species only by selective cutting of stipes.

For a study of colonization on newly denuded rock, 1-m² areas of *L. longipes*, *A. crispa*, and *Hedophyllum sessile* and 0.25-m² areas of *Corallina vancouveriensis* and *Halosaccion glandiforme* were cleared with a shovel, putty knife, and wire brush. Each area was burned twice with a 1 : 1

mixture of fuel oil and white (unleaded) gasoline. For an evaluation of the effects of canopy removal on colonization, the blades and stipes of *L. longipes*, *A. crispa*, and *Hedophyllum sessile* were removed with a wire cutter in 1-m² areas (Table 7).

All plants and animals were removed from a 50-cm(20-in.)-wide strip around each plot to minimize physical disturbance from adjacent algae during surge at high tide and from grazing by benthic invertebrate herbivores (sea urchins, limpets, and chitons). One disturbed plot and one undisturbed control plot were established for each study area.

So that study areas could be located and identified, one corner of each was marked with a 0.3-m length of cord secured with a concrete nail and a numbered washer. Each 1-m² area was divided into four contiguous 0.25-m² plots that were delineated with concrete nails and identified with a numbered piece of survey flagging. Each 0.25-m² area was further marked by an additional concrete nail and numbered washer placed in the corner diagonally away from the cord.

Data were collected from all study areas (experimentally disturbed and control plots) at nearly bimonthly intervals from March 1971 to December 1972, in April 1973, and in August 1973. At each time each 0.25-m² plot was photographed during low tide, and species composition and percent cover were determined for algae on that plot. The photographic sampling frame described in the section Littoral Zonation was used, but the photographs were taken with a 35-mm camera.

Results and Discussion

The sequence of algal species observed on denuded rock benches at Amchitka was (1) dia-

toms and filamentous brown and green algae; (2) ulvoids, i.e., small leafy green algae (*Ulva lactuca* and *Monostroma* spp.); and (3) macrophytic red and brown algae (*Iridaea cornucopiae*, *Halosaccion glandiforme*, *Hedophyllum sessile*, *Alaria crispa*, *Fucus distichus*, *Corallina vancouveriensis*, *Laminaria longipes*, etc.) (see Table 8). Succession observed in areas where the canopy was removed was similar to that indicated earlier, but the rate was faster (Table 9), primarily because they received a lower level of experimental disturbance. In the canopy-removal studies, only *Laminaria* exhibited vegetative growth from its holdfasts, a site of meristematic tissue in this kelp. *Alaria* and *Hedophyllum* plants did not regenerate because their meristematic region occurs in their blades. *Hedophyllum* settled in all areas where the canopy was removed, but *Alaria* settled only in the *Laminaria* zone. For *Alaria* to settle, bare substratum, which was more plentiful in the *Laminaria* zone than in the *Hedophyllum* zone or its own, is required.

Others have noted similar successional patterns (Wilson, 1925; Bokenham, 1938; Northcraft, 1948; Southward, 1956; Dayton, 1971). Bokenham, Northcraft, and Dayton have described various groups of colonizing algae. In general, these are (1) pioneer species (diatoms); (2) fast-growing annuals (ulvoids and *Halosaccion*); (3) fast-growing perennials (*Hedophyllum* and *Alaria*); (4) slow-growing perennials (*Laminaria* and *Corallina*); (5) canopy-producing species, i.e., those which are most successful in competition for light (*Hedophyllum* and *Laminaria*); (6) obligatory understory species, i.e., those which require a canopy to survive or are more often subtidal (coralline algae); and (7) fugitive species, i.e., those which exist in disturbed areas or on the fringes of communities

Table 8—Optimum Algal Colonization Schedule Observed on Denuded Rock Surfaces at Amchitka Island, Alaska, from March 1971 to August 1973

Alga	Season of settlement	Optimum clearing time for rapid recolonization	Period of time before alga is observed	Time to attain at least 75% coverage
Diatoms*	All	All	Within 1 month	1 month
Ulvoids*	All	All	2 to 4 months	2 to 4 months
<i>Iridaea</i> *	Fall and winter	Summer and fall	2 to 4 months	†
<i>Halosaccion</i>	Summer and fall	Fall	4 months	6 months
<i>Hedophyllum</i>	Spring and summer	Fall and winter	4 to 6 months	1 year
<i>Alaria</i>	Winter	Summer and fall	4 to 6 months	4 to 6 months
<i>Fucus</i> *	Summer and fall	Spring and summer	6 to 8 months	14 to 16 months
<i>Corallina</i>	Spring and summer‡	Fall and winter‡	6 to 8 months‡	†
<i>Laminaria</i>	Fall and winter‡	Winter‡	8 to 10 months‡	†

*Settlement did not occur in its own zone.

†Cover never exceeded 18% (see Table 10).

‡Little information is available.

Table 9—Optimum Algal Colonization Schedule Observed in Canopy-Removal Areas at Amchitka Island, Alaska, from March 1971 to August 1973

Alga	Season of settlement	Optimum clearing time for rapid colonization	Period of time before alga is observed	Time to attain at least 75% coverage
Diatoms*	All	All	Within 1 month	†
Ulvoids*	All	All	2 months	2 to 4 months
<i>Iridaea</i> *	All	All	2 months	†
<i>Halosaccion</i> *	Spring, summer, and fall	Spring, summer, and fall	1 month	†
<i>Hedophyllum</i>	Spring, summer, and fall	Summer, fall, and winter	2 to 4 months	11 months
<i>Alaria</i> *	Fall and winter	Summer and fall	2 to 4 months	10 to 12 months
<i>Fucus</i> *	Summer, fall, and winter	Spring, summer, and fall	4 to 6 months	†
<i>Corallina</i>	‡	‡	‡	‡
<i>Laminaria</i>	Fall and winter §	Fall and winter §	2 months §	7 to 9 months §

*Settlement did not occur in its own zone.

†Cover never exceeded 62% (see Table 11).

‡Little information is available.

§Colonization was by vegetative growth.

(*Porphyra* and ulvoids). This last category, suggested by Dayton (1971), is so broadly defined that it could include diatoms, ulvoids, *Halosaccion*, or even *Alaria* at Amchitka.

Most algae that colonized disturbed study areas at Amchitka settled in broader vertical expanses and in more diverse exposures than they normally occupy (Tables 10 and 11). At the indicated exposures to wave action and heights above sea level, the following algae were the most abundant: Diatoms, in all exposures and at all levels; ulvoids, in all areas except those most exposed to wave action; *Halosaccion*, at higher levels in areas of little or intermediate exposure; *Hedophyllum*, in protected areas at lower and intermediate levels; *Alaria*, at lower levels and in exposed areas; *Laminaria*, at lower levels at all exposures; and *Corallina*, in exposed areas at intermediate and lower levels. In general, initial settlement rate was faster in exposed areas at lower levels than in protected areas at higher levels.

Diatoms and ulvoids settled on denuded rock surfaces during all seasons. Their year-round reproductive ability enabled them to occur whenever space was available. All other algae settled on denuded rock during specified seasons (Table 8) when their spores were available. In areas where the canopy was removed, settlement of most species occurred almost throughout the entire year (Table 9). Again this was correlated with the low level of experimental disturbance.

Diatoms persisted for 1 to 8 months after settling, and ulvoids persisted for 5 to 15 months after replacing the diatoms. Peak densities of the

ulvoids occurred in summer on areas disturbed in winter.

Species whose stands were denuded started to colonize their original areas immediately after diatoms and ulvoids disappeared, but only if the area was cleared just before the season when their spores were released and settled, which was inferred from the subsequent appearance of sporelings (see Table 8 for the optimum time period). If a species was cleared too early or too late relative to the time its propagules settled, then any species whose propagules were settling when the diatoms and ulvoids disappeared occupied the area. Thus a *Hedophyllum* plot cleared in December (early winter) was replaced by *Hedophyllum*, and a *Halosaccion* plot cleared then recovered to *Halosaccion*. However, a *Laminaria* plot cleared in the fall contained *Alaria* by spring, and a *Halosaccion* plot cleared in spring contained *Fucus* the following year.

Three of the five species whose stands were denuded and two of the three whose canopies were removed persisted and increased their percent cover when they settled in their own zones. The areas that did not contain at least 80% of the original algal species at the end of our study in April 1973 were the *Laminaria* and *Corallina* denuded areas and the *Alaria* canopy-removal areas. A low reproductive potential may have been responsible for the sparse settling of *Laminaria longipes*. Laboratory experiments (Markham, 1972) indicated little sexual reproduction by this kelp. At Amchitka colonization by *L. longipes* occurred primarily by vegetative growth. As stated

above, the lack of bare substratum probably prevented settlement of *Alaria* in areas where the canopy was removed. *Alaria* and *Hedophyllum* did invade other areas, especially the *Laminaria* plots, and large percent cover values were recorded for these species at the end of the study. Algae that settled outside their normal area will not persist there indefinitely, but it is not known how long it will take the original climax vegetation to establish itself.

Causes of Intertidal Zonation

The results of the colonization studies can now be related to the physical and biological features of the Amchitka environment and can be used to understand the dynamic aspects of the present littoral zonation. Competitive success may be influenced by physical features of the habitat and by biological interactions. Some of the physical stresses typical of littoral communities appear to be relatively ameliorated at Amchitka.

For example, low temperatures, with little seasonal fluctuation, high humidity, and low levels of direct insolation, provide favorable conditions for desiccation-sensitive littoral algae. Other physical stresses, i.e., wave shock and abrasion, also appear to be reduced, as shown by the abundance of species characteristic of protected environments. This protection is due to a reduction in wave action caused by the sheltering effect of offshore kelp beds and by the topography of the intertidal rock benches. Herbivory, an important biological factor in littoral communities, is reduced owing to the reduction of the major herbivores by intensive sea otter predation (Palmisano and Estes, Chap. 22, this volume). The relatively low levels of physical and biological stresses result in a relatively simple system in which the important interactions are probably confined to direct competition for space among algal colonizers.

Each of the species studied in the denudation experiments is a dominant in the Amchitka littoral region and comprises either a zone or an associa-

Table 10—Maximum Percent Cover Attained at Any Time by Intertidal Algae in Five Different Denuded Rock Study Areas at Amchitka Island, Alaska, from March 1971 to August 1973

Algae	Percent cover in denuded rock areas					
	<i>Laminaria</i>	<i>Alaria</i>	<i>Hedophyllum</i>	<i>Halosaccion</i>	<i>Corallina</i>	
	at Makarius Bay	at Duck Cove	at Makarius Bay	at Makarius Bay	at Rifle Range Point	at Duck Cove
Diatoms	100	100	100	100	100	90
<i>Ulva lactuca</i>	100	100	100	100	20	82
<i>Iridaea cornucopiae</i>	18	T*	12	11		T
<i>Halosaccion glandiforme</i>	29	13	66	(100)†	5	95
<i>Hedophyllum sessile</i>	100	58	(100)			
<i>Alaria crista</i>	98	(100)	90	T	100	25
<i>Fucus distichus</i>	89	27	6	75		1
<i>Corallina vancouveriensis</i>	T		T		(10)	(1)
<i>Laminaria longipes</i>	(3)		T			
Filamentous brown	10	100			85	90
Filamentous green	22	79			T	70
<i>Spongomorpha</i> sp.	T		T	T	30	41
<i>Gigartina pacifica</i>	T		T			T
<i>Porphyra</i> spp.	18	T	58	T	5	14
<i>Rhodomenia palmata</i>	36	T	7	11	90	90
<i>Microcladia borealis</i>			T			T
<i>Tokidadendron bullata</i>	T		T		T	
<i>Dumontia simplex</i>	25	8				T
Foliose red‡	35	11	4		2	
Crustose coralline	T	T	T		T	T
<i>Anelopus</i> spp.	9	2		T		T
<i>Scytosiphon lomentaria</i>		13	T	T		T
<i>Leathesia difformis</i>			T			
<i>Petalonia fascia</i>	70		8			7
<i>Cymathere triplicata</i> §	11					

*T, trace, < 1%.

†Circled values indicate the dominant species prior to denudation.

‡Unidentified red alga.

§Upper sublittoral alga.

Table 11—Maximum Percent Cover Attained at Any Time by Intertidal Algae in Three Different Canopy-Removal Study Areas at Amchitka Island, Alaska, from March 1971 to August 1973

Algae	Percent cover in canopy-removal area		
	<i>Laminaria</i> at Makarius Bay	<i>Hedophyllum</i> at Duck Cove	<i>Alaria</i> at Duck Cove
Diatoms	14	56	
<i>Ulva lactuca</i>	78	55	79
<i>Iridaea cornucopiae</i>	5	49	13
<i>Halosaccion glandiforme</i>	39	62	2
<i>Hedophyllum sessile</i>	100	100*	36
<i>Alaria crista</i>	100	3	T†
<i>Fucus distichus</i>	T	35	T
<i>Corallina pilulifera</i>	2	5	5
<i>Laminaria longipes</i> ‡	80		
Filamentous brown	T		
<i>Spongomorpha</i> sp.		T	
<i>Gigartina pacifica</i>	T	T	T
<i>Porphyra</i> spp.	1	T	2
<i>Odonthalia floccosa</i>		T	
<i>Rhodomenia palmata</i>	9	1	T
<i>Microcladia borealis</i>		35	T
<i>Tokiodendron bullata</i>	T	1	
<i>Dumontia simplex</i>		14	4
Foliose red §	7	14	14
Crustose coralline	5	9	
<i>Anelopus</i> spp.		T	T
<i>Scytosiphon lomentaria</i>			T
<i>Leathesia difformis</i>			T
<i>Cymathere triplicata</i> ¶	T		

*Circled values indicate the dominant species prior to denudation.

†T, trace, < 1%.

‡Vegetative growth.

§ Unidentified red alga.

¶ Upper sublittoral alga.

tion. The attributes of these species, which may give them a competitive advantage, can now be considered in view of the results of the colonization studies.

Laminaria species, principally *L. longipes*, characterize a zone in the sublittoral fringe area. A secure holdfast system, round stipes, and long narrow blades may allow them to occupy more exposed areas, but their apparent inability to withstand desiccation probably restricts them to this region of extensive spray. Their dense canopy excludes most other algae except crustose coralline algae from occupying their zone as understory species. The colonization experiments indicate that, when disturbed, *Laminaria longipes* is slow to return unless holdfasts remain from which vegetative growth can take place.

Alaria species, principally *A. crista*, characterize the next higher zone. Their disk-like firmly attached holdfasts and long flat stipes and blades probably enable them to occupy exposed areas, but the flatness of these blades and stipes may not

withstand wave exposure as well as the round stipes and thin blades of *Laminaria* spp. *Alaria* spp. normally occur in areas of slowly receding tides and where there is wave splash. They settle during winter (a season when few species settle) and grow rapidly, both of which characteristics appear to be competitively advantageous. *Alaria*'s dense canopy (and possibly the whiplash effect of their blades) may also help in the competition for space.

Corallina species, particularly *C. pilulifera*, occur throughout the *Hedophyllum* zone, at times in sufficient density to characterize an association within that zone. Their small size and secure holdfasts make them usually an understory species. Their environmental tolerance is apparently quite wide, but they are slow to return when disturbed.

Hedophyllum sessile is a canopy species of sufficient dominance to characterize an association and a zone of its own, the zone that covers most of the middle intertidal bench (Figs. 7 and 11). A weak holdfast, the lack of a stipe, and a large inflexible blade probably exclude *H. sessile* from

the exposed outer edge of the bench but are likely not disadvantageous on the protected middle regions. The colonization experiments indicate that it is a vigorous competitor that quickly recovers from disturbance.

Halosaccion glandiforme is an understory species of the middle bench. Its ability to retain seawater in its thallus during low tide possibly helps it to tolerate desiccation and to occur at high intertidal levels. It may be helped in competition for space by the fact that its spores settle at all times of the year except winter.

Iridaea cornucopiae also characterizes an association within the *Hedophyllum* zone. A perennial alga, it outcompetes *H. glandiforme* (an annual) at higher levels by permanently occupying space and presumably prevents *H. glandiforme* spores from surviving. *I. cornucopiae* occurs in slight depressions that tend to accumulate silt, and thus this tolerance to silt may enable it to outcompete other algae in this area.

The ulvoids, *Ulva lactuca* and *Monostroma* spp., are abundant probably as a result of their spores being available and settling year round.

Fucus distichus characterizes the highest of the midlittoral zones. It not only withstands desiccation well but also it may actually require it. Johnson et al. (1974) showed that *F. distichus* reaches maximum photosynthesis after some degree of drying. It may be absent from lower zones because of increased exposure there (Southward, 1956) and because it requires high light intensities (Gail, 1918) that would be absent under the kelp canopies of lower zones.

Not all species of littoral algae at Amchitka occur in distinct vertical zones. Some species occur in seemingly random places on the intertidal bench or outside their normal location. This suggests the existence of favorable microhabitats or of naturally occurring disturbances that permit their temporary presence.

SUBLITTORAL COMMUNITIES

As emphasized by Wynne (1970a), the statement by Ruprecht (1851, p. 97) that coasts of the Bering Sea are depauperate of algae is "grossly inaccurate." Nowhere is this more evident than in the sublittoral communities. Powers et al. (1960) commented that the floating kelp beds are dense enough to impede transit of small boats. These beds are formed by a single species, *Alaria fistulosa* (Fig. 18). This is the largest species in the genus and is distributed from the southern Kurile Islands to southeast Alaska (Widdowson, 1971a). At Amchitka we saw plants with blades over a meter

Fig. 18—Underwater photograph of the kelp bed at -10 m (-33 ft) near Kirilof Point on Apr. 23, 1972. A dense lower canopy of *Laminaria groenlandica* (broad blades, lower foreground) and a few plants of *Alaria fistulosa* floating toward the surface (upper background) are visible.

in width. We made no measurements of the length of plants owing to collection problems, but we observed that the densest beds occur in water of 5- to 15-m (16- to 46-ft) depth, where by late summer blades of plants often are over 10 m (33 ft) long along the surface. The reports of total blade lengths up to 25 m (82 ft) (Setchell and Gardner, 1903) should be considered minimum for large plants in late summer. At the lowest tides of the year, a few of the shallowest *A. fistulosa* plants may be emersed on seaward-sloping rock benches not dominated by other kelps, but it cannot be considered an intertidal species. The deepest plants were observed at about 20-m (66-ft) water depth. On the shallow Pacific coast, beds may be seen several kilometers offshore. These beds have a great damping effect on waves. In moderate seas, there is usually only gentle surging on a coast behind these beds. This is probably a major reason for the relatively protected aspect of the littoral communities at Amchitka.

As seen at the surface, *A. fistulosa* beds are small in winter, but by late summer they reach a peak of density, and much of the nearshore area is covered. This change results from the growth of individual plants, at least some of which persist through the winter. It is also brought about by an increase in population size in the spring. Since we

did not conduct a tagging study, the longevity and population turnover of these plants were not determined. Most of the population may be annual with few plants remaining throughout the winter; however, winter storms may break off the floating fronds but leave the holdfasts intact to produce new blades the following spring. Other species of *Alaria* are perennial and have a peak of summer growth (Widdowson, 1971a).

Specimens of *Nereocystis luetkeana*, the well-known floating kelp of the West Coast of the United States, are commonly found drifted onto the beaches of Amchitka and a few have been found tangled in offshore kelp beds, but no attached *Nereocystis* plants have been observed at Amchitka. The same situation occurs in the Commander Islands (Kardakova-Prezhentsova, 1938). These plants must drift along the Alaska Stream current from the westernmost point of its known distribution, Unalaska Island (Druehl, 1970), or from points still farther east.*

Beginning with the *Laminaria longipes* population on the intertidal bench and extending down to about 20-m (66-ft) depth, there is a continuous cover of the solid-rock bottom by various kelp species (Fig. 19). In some areas *L. longipes* extends in beds down to about 3-m (10-ft) depth. In other areas and extending down to depths of 10 m (33 ft) or more, *L. dentigera*, *L. groenlandica*, *L. yezoensis*, *Alaria* sp., and *Thalassiophyllum clathrus* make up the dense kelp canopy. *Cymathere triplicata* is present on boulders in shallow water, and *Agarum cribrosum* occurs with increasing frequency until it dominates the solid-rock substrate at about 20-m (66-ft) depth.

The morphology of some of these kelps, with long 50- to 100-cm (20- to 40-in.) stipes, allows for a dense understory of a rich red algal flora (Weinmann, 1969). Notable among the species are *Ptilota asplenoides*, *P. filicina*, *Hypophyllum ruprechtianum*, *Cirrularia gmelini*, and *Constatinea rosa-marina*.

Finally, the very lowest of the floral elements is that of the crustose species, particularly *Codium ritteri*, *Lithothamnium* spp., *Mesophyllum aleuticum*, and *Clathromorphum* spp. This element begins at the lower edge of the *Laminaria longipes* beds and extends far below the kelp cover to well over 30 m (98 ft). At these depths, the limit of our scuba diving effort, *Clathromorphum nereostratum* dominated the bottom, and its lower limit has not been ascertained.

Observations of marine algal populations in sublittoral plots at 5- and 9-m (16- and 30-ft)

Fig. 19—Underwater photograph of the shallow kelp bed at -1 to -2 m (-3 to -7 ft) near Kirilof Point on Apr. 23, 1972. *Laminaria longipes* (upper) and *Thalassiophyllum clathrus* (lower right) are dominant. The broad blade in the center is probably *Laminaria yezoensis*.

depths 9 months after selective removal of the dominant kelps indicated that strong competitive interactions influence algal distributions in these populations (Dayton, 1975). Predation by sea otters on algal herbivores has been suggested as the major reason for the dense algal populations in the Amchitka sublittoral region. Dayton concluded that the larger *Laminaria* species are competitive dominants and that *Alaria fistulosa* behaves as a fugitive species. He suggested that the removal of *Laminaria* spp. by wave shock in shallow areas and selective grazing by sea urchins in deep areas explain the general distribution of kelp species in sublittoral communities at Amchitka (see Palmisano and Estes, Chap. 22, this volume).

PHYTOGEOGRAPHY AND FLORISTICS

Lebednik et al. (1971) examined the geographical distributions of the marine algae identified from Amchitka up to 1970. Each species was classified into one or more of the following groups: endemic; western North Pacific; eastern North Pacific; and Arctic-Atlantic. The percentages of the total number of species within each group are shown in Table 12, which indicates that the Amchitka flora has strong affinities to the three major surrounding regions. Whether the "endemic"

*However, E. S. Zinova (1940) stated that *Nereocystis* plants were found attached in the Commander Islands.

Table 12—Floristic Affinities of the Amchitka Marine Algal Flora Expressed as Percentages of the Total Number of Amchitka Species (69) Reported from Surrounding Regions*

Percent	Region
22.8	Atlantic—Arctic coasts
49.3	Western North Pacific coasts
39.2	Eastern North Pacific coasts
10.1	Endemic to Bering Sea islands (including Aleutians)

*Based on species identified as of 1970 (some species occur in two or three regions).

species are truly limited in distribution or are not known elsewhere because of lack of comparable collections, especially in the sublittoral region, cannot be deduced at this time.

Wynne (1972) found that three of the nine species of *Porphyra* found on Amchitka have a circumboreal distribution. The other *Porphyra* species showed affinities both to the Japanese flora and to the American flora, in agreement with the overall distributions reported by Lebednik et al. (1971). We have not attempted to reexamine the overall floral affinities of the Amchitka marine algae using the expanded list of 117 species now known from the island (see Table 2) because of the difficulty of assessing the identifications in the older literature and of the application of recent taxonomic changes to wide geographical areas. Many algal groups have not received critical taxonomic attention. There is a great need for systematic studies that include collections from the Asiatic and North American coasts as well as from the Aleutian Islands. Following these studies it will be possible to make more definitive statements concerning the floristic affinities of the Amchitka flora.

Wynne (1970a) showed that the development at Amchitka of the Delesseriaceae, order Ceramiales, is diverse. Of the 16 species recognized from Amchitka, 6 were newly described* and 1 was placed in a new genus, *Zinovaea*. Wynne (1970b) also described another new genus, *Pleuroblepharis*, in the family Bonnemaisoniaceae, order Nemaliales.

The taxonomy and distributions of the coral-line genera *Clathromorphum* and *Mesophyllum* were examined by Lebednik (1973). Of the species occurring at Amchitka, *C. circumscriptum* and *C.*

compactum occur in the North Pacific Ocean northward from Hokkaido, Japan (Adey, Masaki, and Akioka, 1976), and Baranof Island, Alaska. Both extend into the Arctic and North Atlantic Oceans. *Clathromorphum loculosum* is known only from the northern Bering Sea, Commander and Aleutian Islands, and southward to Baranof Island, Alaska. The epiphyte *C. reclinatum* occurs widely in the North Pacific Ocean, from Hokkaido and Sakhalin in the west to southern California in the east. Two new species were described from Amchitka: (1) *C. nereostratum*, a massive plant covering large areas of the Amchitka sublittoral region, and (2) *Mesophyllum aleuticum*, one of two species in the genus to be found at Amchitka (the second species is not yet named and is still under study). *C. nereostratum* is known from the Aleutian and Kurile Islands, and *M. aleuticum* has been collected at the Alaska Peninsula as well as in the Aleutians. It was concluded that the center of distribution of *Clathromorphum* (which was based on concentration of number of species) is in the Aleutian Islands. These initial taxonomic studies suggest that, when the Amchitka collections of other groups of marine algae are studied in detail, more new species and genera are likely to be described.

EFFECTS OF UNDERGROUND TESTING ON MARINE ALGAE

The Milrow and Cannikin tests affected littoral communities principally by permanently uplifting coastal areas. The mortality and subsequent recovery of littoral vegetation were studied in these disturbed areas.

Methods

The effects of the Milrow test were studied by 0.25-m² quadrats straddling a fault line at Duck Cove on the Pacific Ocean coast (IA-1). The effects of the Cannikin test were studied by placing 51 plots (8 of the original 40 were destroyed and 11 were established after the test) in the major species associations in two areas (IA-2 and IA-3) on the Bering Sea coast. All these plots were permanently marked and photographically sampled as described earlier for T-1 and T-2. In addition, 15.4 km (10 miles) of Bering Sea coast, centered approximately at IA-2, was surveyed by visual observation at low tide once before the Cannikin test and twice afterward.

Milrow-Affected Areas

Lebednik (1973) reported the effects of the nuclear test Milrow, which caused a fault shift

**Asterocolax hypophyllophila*, *Hypophyllum dentatum*, *Laingia aleutica*, *Neinburgia prolifera*, *Phycodrys amchitkensis*, and *Zinovaea acanthocarpa* (see also footnote, p.358).

resulting in an uplift of about 12 cm (5 in.) of an intertidal area (Fig. 20) of about 4 ha (10 acres) on the Pacific Ocean coast. The uplift caused die-off in certain algal populations, especially those of the *Hedophyllum* zone. Twenty-five species were observed in plots on the uplifted portion of the bench. Seventeen of these species were so infrequent or sporadic that any possible effects could not be deduced in their populations. Of the eight most frequent species for which effects could be observed, five showed mortality attributable to the uplifting, one (*Fucus distichus*) increased significantly in frequency, and the remaining species exhibited little change in frequency (Fig. 21). Most die-off occurred in the first 6 months after the test. Lebednik (1973) concluded: "The rather rapid and extensive die-off suggests that the populations affected were vertically close to their upper physiological limits before the uplifting. . . ." Continued sampling of the area indicates a gradual shift of algal species. Three and one-half years after the test (in early 1973), major increases in the *Fucus* and *Alaria crispa* populations were still occurring in 64% of the plots (Nakatani and Burgner, 1974). This confirms Lebednik's (1973) prediction that the die-off in the *Hedophyllum* zone would be followed by formation of a *Fucus* zone. There is no doubt that a stable algal community will eventually be established.

Cannikin-Affected Areas

The 1971 Cannikin test caused an uplift of as much as a meter along the Bering Sea coast. Two areas with fixed plots (IA-2 and IA-3, see Fig. 26) were located in the area most affected by the test. An average uplift of 91 cm (36 in.) occurred in the IA-2 study area (Nakatani et al., 1973; 1974). An indication of the damage caused is given in Fig. 22, which shows a portion of the IA-2 area. The upper photograph was taken in August 1970 (15 months before Cannikin), at which time the rock bench in the foreground was completely covered by *Halosaccion glandiforme*, *Rhodomenia palmata*, and *Corallina* spp. The surge channel at the center was dominated by *Alaria crispa* and *Laminaria longipes*, and, between this area and the sea stack, a varied vegetation of *Hedophyllum sessile* and *Laminaria longipes* was dominant in low pools. The lower photograph was taken in April 1973 during an equivalent low tide. More rock was exposed both in the surge channel and in reefs behind the stack. A great deal of rockfall from both the stack and the adjacent sea cliff had buried some intertidal areas, including three study plots. Of greater significance was the complete lack of algal vegetation on the rock benches. In the surge channel the

Fig. 20—View of the IA-1 area at Duck Cove. The fault runs across the center of the intertidal bench. To the left the bench was uplifted; to the right no elevation change occurred. Photograph was taken on Mar. 29, 1971, at a -30-cm (-12-in.) low tide.

algae that had settled since Cannikin were limited to areas below the 1970 low-water line, and the only other vegetation visible was on the offshore reefs behind the sea stack.

Following the uplifting, *Iridaea cornucopiae* was the first species to show conspicuous mortality. By April 1973 all the 20 surviving plots (5 more had been buried by rockfalls), which preshot were representative of the entire vertical range of intertidal vegetation, were devoid of algae except for a few *Porphyra* sp. and green algal plants. Total destruction of littoral vegetation also occurred in other areas with comparable uplifting (Nakatani and Burgner, 1974).

At IA-2 the sublittoral region, including the sublittoral fringe, was lifted to a new level, and a new littoral vegetation is expected to develop. The shallow sublittoral fringe is one of the most difficult areas to sample because it is mostly underwater even during low tides, and knowledge of the sublittoral communities occurring there has been limited (Weinmann, 1969). The uplifting of Cannikin allowed observations of these communities. At the IA-2 area a large portion of the kelp community was occupied by three *Laminaria* species: (1) *L. longipes*, (2) *L. groenlandica*, and (3) *L. yezoensis*. *Thalassiophyllum clathrus* was present in some localities, and *Alaria fistulosa*, which forms the extensive offshore floating kelp beds fringing the island, was abundant on one rock bench at the lowest level exposed by the uplift. These species and their associated flora, except for *Laminaria longipes*, wherever they had been lifted into the intertidal area, were dead by April 1973.

Fig. 21—Summary of frequencies of the eight most frequent species (except *Analipus filiformis*) on the uplifted plots at IA-1 in 1970. Z, deduced pretest pattern. A, April. M, May. S, September. [From P. A. Lebednik, *Marine Biology*, 20: 201 (1973).]

New plots were established at IA-2 after Cannikin in four types of habitat: (1) High outer bench, (2) surge channel basin, (3) newly exposed rock, and (4) low outer bench.

Two plots in the first habitat were located on the outer portion of the intertidal bench at a relatively high level. This was an area exposed to heavy wave action; the pretest vegetation was characteristic of the lower levels. The reaction of *Laminaria longipes* at a relatively protected plot (Fig. 23) is compared with that of a more exposed population (Fig. 24). In vegetation the plots were identical initially and followed generally the same pattern of decrease in cover. However, some plants remained alive 2 months longer on the more exposed plot, and the remains of dead plants were still visible 17 months after Cannikin. The exposure conditions have changed because the outer vertical face of the bench is well above mean lower low water and does not allow wave splash on the bench top as it did pre-Cannikin except during the highest tides. Should any new vegetation develop on these plots, there should be a significant difference between the two.

Two new plots were established in the bottom of a surge channel basin where the stable substrate

is large boulders. In both plots the pre-Cannikin vegetation was dominated by a tall dense canopy of *Laminaria yezoensis*, beneath which was a dense stand of *L. longipes*, covering most of the rock. Although the entire *L. yezoensis* population died,

Fig. 22—View eastward at IA-2 in August 1970 (upper) pre-Cannikin and April 1973 (lower) post-Cannikin.

Fig. 23—Percent cover of *Laminaria longipes* versus time at IA-2 (dead cover of *L. longipes* indicated by shading), December 1971 to April 1973. Preshot elevation, 34.3 cm (14 in.); postshot, 122.1 cm (48 in.); uplift, 87.8 cm (35 in.).

Fig. 24—Percent cover of *Laminaria longipes* versus time at IA-2 (dead cover of *L. longipes* indicated by shading), December 1971 to April 1973. Preshot elevation, +58.3 cm (23 in.); postshot, +153.2 cm (60 in.); uplift, 94.9 cm (37 in.).

L. longipes, which initially showed some die-off, began to recover in August 1972 (9 months after Cannikin), as illustrated in Fig. 25. *Laminaria longipes* normally occurs in the sublittoral fringe, and its survival here is consistent with the present elevation of these plots.

Succession on newly exposed rock surfaces was studied in three plots. Two of them were on the vertical surface that formed the outer face of the pre-Cannikin intertidal bench and one was on the horizontal surface of a large rock boulder immediately seaward of the other two. All these plots showed a similar pattern of colonization. Three

Fig. 25—Percent cover of *Laminaria longipes* versus time at IA-2 (dead cover of *L. longipes* indicated by shading), February 1972 to April 1973. Preshot elevation, -93.2 cm (-37 in.); postshot, 1.7 cm (1 in.); uplift, 94.9 cm (37 in.).

months after Cannikin, two species were present: (1) A large population of *Cladophora* sp. and (2) numerous plants of *Porphyra* sp. (*P. pseudo-linearis*?). Two months after that, in April 1973, both species had decreased in cover whereas *Halosaccion glandiforme* had become dominant in two plots and *Rhodomenia palmata* in one. *Alaria crista* had appeared in two of the plots; this was the first indication of the appearance of a kelp canopy.

The four plots established in the final habitat were on a low rock bench with a uniform seaward slope that was subtidal pre-Cannikin but became intertidal post-Cannikin. Observations after the uplifting indicated a threefold preshot zonation from landward to seaward dominated by *Laminaria longipes*, *Thalassiophyllum clathrus*, and *Alaria fistulosa*-*Laminaria groenlandica*. The first two dominants were represented by one plot each and the last one by two plots that reached to the outermost portion of the bench emerged at low tide. By April 1973 the *L. longipes* population had died in the plot originally dominated by it. During 1972 *Rhodomenia palmata* appeared and reached a maximum in October 1972 but still was abundant (64%) in April 1973. The appearance of *Fucus distichus* and *Alaria crista* in April 1973 signaled the reestablishment of a kelp canopy in the plot. At the plot where *T. clathrus* was the dominant species pre-Cannikin, *Rhodomenia palmata* initially showed an increase but was soon covered by a burgeoning *Alaria crista* population that first appeared in June 1972 and occupied 100% of the plot by April 1973. At the outermost plots *Laminaria longipes* settled and dominated one (75%) and *Alaria crista* dominated the other (80%). *Rhodomenia palmata* was fairly abundant in these two plots in June and August 1972 before its populations were covered by the growing kelp plants.

The second area, IA-3 (Fig. 26), established to study effects of Cannikin, had only 13 plots survive after Cannikin since 2 of the original plots were buried by rockfall. Although the IA-3 area underwent an average uplift of only 50 cm (20 in.) as compared with 91 cm (36 in.) at IA-2, mortality was nearly as complete. As of April 1973, five plots had no live algae; eight had one or both of two *Porphyra* species; *Ulva lactuca* occurred on three plots; and *Rhodomenia palmata*, *Anelopus filiformis*, and *Halosaccion glandiforme* each occurred on one plot in insignificant amounts. Only at one plot, where a small *Fucus distichus* population had settled and started to develop, was there an indication of permanent colonization. Except for this last plot, no midlittoral vegetation colonized the IA-3 plots after the Cannikin test. New

Fig. 26—Location of points discussed in the Bering Sea coast survey.

plots were not established at IA-3 to document colonization, but we did make general observations. By April 1973 there was heavy *Fucus distichus* colonization just below the original plots. *Alaria crista* appeared to be newly abundant and dominant near low water levels [at the -0.5 -m (-2 -ft) tidal level]. There was little evidence of *Laminaria longipes* or *Hedophyllum sessile*.

So that the data taken at the IA-2 and IA-3 plots could be generalized, observations were made at low tide along the 15.4-km (10-mile) stretch of shore between Sea Otter Point and Crown Reefer Point (see Geological Survey map in the pocket at the back of this volume). Walks were made in August 1971, $2\frac{1}{2}$ months before Cannikin, and in April 1972 and 1973, 5 and 17 months afterward (Table 1).

The observations made in April 1972 on algal die-off on this stretch of shore are summarized in Fig. 27. Coastal landslides were visible west of Petrel Point, but algal die-off did not become apparent until just east of Petrel Point. From there to point 9B, die-off was light and patchy. Between points 9B and 10B, die-off was more extensive and involved more species. From just west of point 10B to the mouth of White Alice Creek, die-off was extensive and comparable to that at IA-2 except that near where the creek flowed over the bench *Iridaea cornucopiae* appeared to be less affected. East of White Alice Creek to point P8, die-off was moderate and discontinuous. At Banjo Point only the *Alaria* zone showed die-off. Elsewhere portions of the populations of *I. cornucopiae*, *L. longipes*,

and crustose coralline algae showed die-off. Eastward from point P8 to point 96B, only *I. cornucopiae* and *L. longipes* mortality was observed, and beyond point 96B no test-related die-off was seen at all.

Severe damage was observed along 1.9 km (1 mile) of shore, including the IA-2 and IA-3 areas. Moderate damage was seen on 1.5 km (1 mile) of shore and damage detectable along 2.7 km (2 miles) of shore. Altogether, 6.1 km (4 miles) of shore was affected.

In April 1973, except for a slight increase in mortality around Petrel Point, the distribution of mortality was similar to that in April 1972. Dead plants not yet removed by wave action made it difficult to detect colonization in the moderately affected areas. In the severely affected areas, colonization occurred as reported for IA-2.

Fig. 27—Alongshore die-off of littoral algae due to Cannikin, April 1972.

Following the field studies of Lebednik, observations of the IA-2 and IA-3 areas were made in May and August 1974 by other FRI staff members and were reported by Kirkwood (1974; 1975). No quantitative data on cover values of the species were presented; however, significant changes in species composition appear to have occurred since August 1973 in 8 of the 11 plots discussed previously. It is estimated that the total area of intertidal bench uplifted into the supralittoral fringe by Cannikin was 5.8 ha (O'Clair, Chap. 18, this volume).*

The effects of uplifting from underground testing at Amchitka and those of uplifting from the Alaska earthquake of 1964 as reported by Johansen (1971) were similar. In both localities littoral populations did not tolerate the environmental conditions at higher elevations and extensive mortality resulted. A subsequent succession of species in the disturbed areas led eventually to a return to the original pattern of zonation, which was consistent with the new elevations and changes in exposure.

Uplifting at Amchitka will probably have a significant long-term effect because of the presence of flat rock benches in the midlittoral region. These benches were lifted above the midlittoral region at IA-2 and IA-3 following the Cannikin test. A new midlittoral vegetation in those localities will have far less area on which to develop. Because the supralittoral fringe populations depend on wave splash, which occurs only at the edge of the benches, only a small portion of the bench area will be colonized by these species.

Mortality may occur over a period of months in uplifted populations, depending on the habitat and amount of uplifting. The early stages of colonization appear to be strongly influenced by seasonal spore production. A disturbed plot may remain nearly devoid of algae or with unchanged vegetation during the winter months but may exhibit rapid changes in species composition and abundance in the spring. The return to a normal community may require years, as exemplified by the marked changes in the *Fucus* populations at IA-1 3½ years after the Milrow test and the changes observed in Cannikin-disturbed areas nearly 3 years after that test.

SUMMARY

The climate, sea conditions, and topography of Amchitka Island are favorable for the development

of an abundant and diverse marine algal flora. A review of phycological research in the North Pacific Ocean, in particular that of Russian workers, indicates a dearth of knowledge of the marine algal flora of the Aleutians.

A somewhat unusual topographic feature, extremely flat rock benches, occurs at about mean tide level around the southeastern third of the island. These benches provide an exceptionally large area for the development of littoral vegetation. The seaward edge of the bench, where waves are often breaking, is the most exposed portion, whereas the landward edge is usually quite protected. Cloud cover and humidity are very high throughout the year, and thus the littoral algae do not experience much desiccation. Air temperatures are generally about the same as seawater temperatures except that in the winter subfreezing conditions prevail for short periods. Heavy wave action is characteristic of Amchitka. Seawater temperatures range from 2 to 10°C at the shore, and the water is exceptionally clear. The extensive rocky areas, cool moist climate, and clear water conditions provide an ideal environment for marine algae.

The littoral marine vegetation was studied by means of two transects, one each on the Pacific Ocean and Bering Sea coasts. The littoral region can be classified into the supralittoral fringe and midlittoral areas. The supralittoral fringe is composed of three zones, from top to bottom: (1) *Prasiola*, (2) *Rhodochorton*, and (3) *Porphyra-Ulothrix*. The last zone is practically absent in the fall and winter and reaches its highest development in late spring and summer. The upper limit of the midlittoral area, usually taken as the upper limit of the barnacle zone, was assigned to the upper limit of the *Fucus* zone owing to the lack of a barnacle zone at Amchitka. The next lower zone is a *Hedophyllum* zone that usually occupies the greatest area because its occurrence coincides with the level of most of the rock benches. Six associations can be recognized within the *Hedophyllum* zone: (1) *Ulva*, (2) *Analipus*, (3) *Corallina*, (4) *Halosaccion*, (5) *Hedophyllum*, and (6) *Iridaea*. The greatest number of species and the most complex vegetation were observed in this zone. The third zone of the midlittoral area, the *Alaria* zone, occurs primarily near the outer edge of the benches. The sublittoral fringe consists of the *Laminaria longipes* zone, in which several sublittoral species have their upper limit. Tide pools are rare, but channels running across the benches and connected with the sea at low tide have a sublittoral flora. The bench topography influences littoral vegetation in that the distribu-

*Previously reported as 57.6 ha (Kirkwood, 1975).

tions of many species were correlated with horizontal distance perpendicular to the shore regardless of elevation. Seasonal photographic sampling indicated that most littoral species occur throughout the year. Most species appeared to release spores in late winter—early spring, and the appearance of sporelings follows this period. Growth of sporelings as well as of older plants reached a peak in late spring—early summer. The *Porphyra-Ulothrix* zone and the *Halosaccion* association were annual, occurring from early spring to late summer. The littoral zonation was nearly identical to that described at the Commander Islands and was similar to that described at the northern Kurile Islands. The zonation at Amchitka was also compared with that of southeastern Kamchatka, Sakhalin Island, Hokkaido, Japan, and the Strait of Juan de Fuca.

Total removal of organisms from rocky intertidal plots resulted in a colonization sequence of diatoms and filamentous algae, leafy green algae, and larger red and brown algae. In plots where only the kelp canopy had been removed, the sequence was similar but faster. Initial settlement occurred most quickly in exposed areas at low levels. Colonization was strongly influenced by the length of time between the clearing of plots and the next annual spore release of the species originally dominant in that plot. Three of the five species whose stands were denuded and two of the three whose canopies had been removed attained a coverage of at least 80% in their own zone by the end of the study. Those which did not attain this degree of coverage were *Laminaria longipes* and *Corallina vancouveriensis* in denuded areas and *Alaria crispa* in areas where the canopy had been removed. The low recovery of *L. longipes* was attributed to its low degree of sexual reproduction. The scarcity of *A. crispa* was attributed to the lack of bare substratum needed for settlement. The establishment and maintenance of algal zones and associations, at times in almost pure stands, are enhanced by the physical homogeneity of the intertidal bench, the relatively few species of dominant algae, and the lack of excessive physical and biological disturbances.

The sublittoral communities are extremely dense. *Alaria fistulosa*, which forms huge floating kelp beds, was observed down to about 20 m (66 ft). These kelp beds have a considerable damping effect on wave action. A dense covering of kelp occurs on the bottom from the intertidal area down to about 20 m (66 ft) and was formed by species in the genera *Laminaria*, *Thalassiphyllum*, *Cymathere*, *Alaria*, and *Agarum*. A third level of vegetation is made up of filamentous and foliose

red algae, such as *Ptilota asplenioides*, *P. filicina*, *Hypophyllum ruprechtianum*, *Cirrularia gmelini*, and *Constantinea rosa-marina*. The fourth level of vegetation, consisting of crustose forms and extending well below 30 m (100 ft), included the green alga *Codium ritteri* and the coralline genera *Clathromorphum*, *Lithothamnium*, and *Mesophyllum*. The richness and density of marine algae at Amchitka might be due to the removal of invertebrate herbivores by sea otters. A strong relationship between the Amchitka flora and the western Pacific, eastern Pacific, and Arctic floras was found by comparing species lists. The initial results of a long-term taxonomic study have resulted in the description of three new genera and eight new species from Amchitka.

The Milrow nuclear test caused a 12-cm (5-in.) uplifting of a portion of intertidal bench totaling about 4 ha (10 acres). Mortality ensued in the upper portions of all zones, especially the *Hedophyllum* zone, within 6 months after the test. Although new vegetation characteristic of the higher levels had begun to develop, significant changes were still observed in some plots 3½ years after the test. The Cannikin test caused a maximum uplift at the shore of about 1 m (3 ft), which occurred in one of two study areas. Total mortality of all algal species ensued in both study areas with uplifting of 0.5 to 1 m (1.5 to 3 ft) and along 1.9 km (1 mile) of coastline. Moderate mortality was observed along an additional 1.5 km (1 mile) of coastline, and some mortality was detected for a further 2.7 km (2 miles). A total of 6.1 km (4 miles) was affected. New plots were established in formerly sublittoral areas, and colonization was followed. Significant changes were occurring in these plots when last observed, nearly 3 years after the test. As was the case with the Milrow-disturbed areas, new vegetation was forming in consonance with the new elevations and exposure of the disturbed areas. In contrast to the Milrow disturbance, which will have no long-term effects, the Cannikin disturbance has resulted in a marked reduction of area at midlittoral levels by permanent lifting of the intertidal bench into the supralittoral fringe. Supralittoral fringe species, which require constant wave splash, will be able to colonize only the outer edges of the uplifted benches.

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Marine Invertebrates in Rocky Intertidal Communities

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Previous knowledge of Aleutian marine benthic invertebrates was based on few observations and collections, the history of which is summarized. In this study three belt transects (one sampled once and two sampled seven times) and two intertidal arrays (sampled twice each) of 0.25-m² quadrats were used for descriptive studies of intertidal communities at Amchitka Island. These communities are dominated by algae at all tidal levels. Three communities designated according to their dominant macrophytes are the Laminaria community, the Alaria-Hedophyllum community, and the Halosaccion-Fucus community. Invertebrates in these communities are mostly inconspicuous. Despite the large proportion of North American species in the fauna of Amchitka, species that play key roles in structuring intertidal communities elsewhere on the west coast of North America are absent or in low abundance at Amchitka. Invertebrates in sublittoral communities are discussed briefly. An annotated list of over 365 littoral and sublittoral invertebrate species is appended.

The marine invertebrate fauna of the Aleutian Islands has received little attention beyond the initial taxonomic descriptions that have followed mainly the collecting activities of E. Wosnesenski and W. H. Dall. Except for the pioneering work of Gurjanova (1935; 1966) on Bering Island (Ostrov Beringa) and the brief description by Barabash-Nikiforov (1947) of the benthic fauna at Copper Island (Ostrov Mednyi) in the Commander Islands (Komandorskie Ostrova) (Fig. 1), little has been published on the ecology of Aleutian benthic marine invertebrates. Some ecological information can be gleaned from those systematic monographs which have included collections from the Aleutian Islands (see history of previous investigations below), but it is chiefly anecdotal and incomplete.

Here I describe some patterns of distribution and abundance of invertebrates in rocky intertidal communities at Amchitka Island, Alaska, and note

Seven zoogeographical elements were recognized in the shallow-water marine fauna of Amchitka. The greatest proportion of species are North Pacific or North American in their distribution. Two oceanographic features (the Alaskan Stream and the Kamchatka Current) and one geologic feature (the Aleutian "stepping-stone" islands between Amchitka and the Asian and North American mainlands) increase the immigration rates of North American species over Asiatic species.

The effects of Cannikin were determined with the use of two intertidal arrays of fixed 0.25-m² quadrats (totaling 40 plots) examined twice preevent and ten times postevent (over 33 months) and an intertidal grid (control) sampled randomly once preevent and twice (over 9 months) postevent. The rate of die-off and emigration of intertidal species in maximally uplifted (as much as 1 m) areas depended on exposure to open ocean waves. Most preevent intertidal species were replaced by supralittoral fringe species.

some of the salient differences in community structure between these communities and other comparable North Pacific intertidal communities. Descriptive studies alone provide little insight into community organization, and they have largely been replaced by approaches of a comparative or experimental nature. I justify a descriptive approach here by pointing out the absence of a previous detailed study of Aleutian intertidal communities and by noting the peculiarities of the intertidal communities at Amchitka. Detailed descriptive studies are not necessary prerequisites for mechanistic studies, especially when the community can be observed directly. However, at Amchitka patterns of invertebrate distribution and abundance are not obvious; invertebrates are usually inconspicuous, and patterns in the distribution of populations are obscured by dominant macrophytes.

I also discuss the zoogeographical affinities of three major taxa of littoral and shallow sublittoral [to a depth of 60 m (200 ft)] invertebrates (Polychaeta, Crustacea, and Mollusca) at Amchitka and

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Fig. 1—Map of the northern North Pacific Ocean and Bering Sea showing the location of Amchitka Island, Alaska, the Alaskan Stream (information from Favorite, 1967), and the Kamchatka Current (information from Dodimead, Favorite, and Hirano, 1963).

describe the most destructive and long-lasting effects on some rocky intertidal communities due to uplift of the intertidal benches by the underground nuclear test, Cannikin.

PREVIOUS INVESTIGATIONS IN THE ALEUTIANS

Georg Wilhelm Steller's important contributions marked the beginning of zoological investigations in the North Pacific. We do not know whether Steller collected or described invertebrates from Bering Island, the only Aleutian island on which he set foot, because most of his collections from Bering Island and his manuscripts on invertebrates were lost (Stejneger, 1936). We do know that he collected and described invertebrates from Kamchatka, e.g., *Cryptochiton stelleri** and *Mya*

truncata. Steller and those early naturalists who came after him (Merck, Sauer, Tilesius, Chamisso, Eschscholtz, and Mertens) into this region during the late eighteenth and early nineteenth centuries participated in expeditions whose primary mission was to discover and explore new lands. The opportunities for naturalists to make observations on the shores of this region were limited. When it was possible to go ashore, their attention was drawn to the more obvious flora and fauna, such as marine mammals, birds, and the more conspicuous terrestrial plants. The only publications on Aleutian invertebrates that emerged from these early expeditions were very brief descriptive accounts of the fauna of one or two islands (Sauer, 1802; Chamisso, 1821) and some taxonomic work (Chamisso and Eysenhardt, 1821; Eschscholtz, 1833).

The first real scientific documentation of Aleutian invertebrates came about the middle of the nineteenth century in the taxonomic works of Middendorff (1846; 1849a; 1849b; 1849c; 1851), Brandt (1849; 1850; 1851), and Grube (1855), which describe several species collected in the Aleutians primarily by E. Wosnesenski. Prior to Wosnesenski's excursions, which extended to Atka and Attu Islands, invertebrate collecting had been limited to the ends of the Aleutian chain, espe-

*Dall (1884) states that specimens of *Cryptochiton stelleri*, described by Steller under its Kamchatkan name "Keru," were collected by Steller on Bering Island. Dall cites as his reference Steller's *Beschreibung von dem Lande Kamschatka*; however, I could find no reference to Bering Island in Steller's description, and Middendorff (1846) lists only Peter and Paul (Petropavlovsk) Harbor in Kamchatka as the collection locality of *C. stelleri*.

cially around Unalaska in the east and the Commander Islands in the west.

The greatest contribution to our knowledge of Aleutian invertebrates has come from William H. Dall, whose assignments in the Aleutians under the U. S. Coast Survey from 1871 to 1874 enabled him to make collections on a number of islands, including Amchitka, from which invertebrates had not previously been collected. Dall subsequently described most of the species he had collected, especially the mollusks (see Boss, Rosewater, and Ruhoff, 1968). Collectively, these publications on the systematics and zoogeography of Aleutian mollusks constitute the definitive source of information on this the best known group of Aleutian invertebrates. In addition, Dall's collections have provided most of the Aleutian littoral material for a number of publications on other invertebrate groups: hydroids (Clark, 1876), barnacles (Pilsbry, 1916), isopods (Richardson, 1905), starfish (Fisher, 1911; 1928; 1930), and others.

After Dall, collecting activity was again mostly restricted to the eastern and western ends of the Aleutian chain. Investigations near the eastern end of the Aleutians have included the trawling and dredging activities of the U. S. Fish Commission steamer *Albatross* in the waters from Unimak to Umnak Islands in 1888, 1890, and 1893 and the Harriman Alaska Expedition in the vicinity of Unalaska in 1899. At the western end of the chain, the Commander Islands were visited by the *Vega* expedition under Nordenskiöld in August 1879; by Stejneger under the auspices of the Smithsonian Institution and the U. S. Signal Service in 1882, 1883, and 1895; by the *Albatross* in 1892, 1895, 1896, and 1906; and by several Russian naturalists (see Gurjanova, 1935). However, some collections were made near Amchitka. They include those made by investigators on board the *Albatross* at Kiska Island in 1894 and near Semisopochnoi Island in 1906 and by V. Scheffer aboard the *Brown Bear* in 1937 at Amchitka. More recently, Newell (1950; 1951) and Yamada (1955) have published on collections from this area.

Despite all the collecting activity, very little has been published on the ecology of Aleutian benthic invertebrates. Dall (1884) and Annenkova (1934) have provided some information on the natural history of the littoral mollusks and polychaetes of Bering Island, but their publications were primarily taxonomic in nature. The studies on the distribution of algae and invertebrates at Bering and Mednyi Islands by Gurjanova (1935; 1966) and Barabash-Nikiforov (1947), respectively, represent the only published attempts to deal with the benthic communities of any Aleutian island.

PHYSICAL ENVIRONMENT

Tides

The most important phenomenon ultimately controlling the lives of most littoral invertebrates is the tidal cycle. The amplitude and frequency of tidal fluctuations determine the length of time a particular level on the shore is either submerged or exposed to atmospheric conditions, which, in turn, generally determines, directly or indirectly, whether a species can maintain a population at that level. For example, the upper limit of distribution of a particular species may be determined directly by the amount of time it is subject to the stress of desiccation; at the same time its lower limit may be set indirectly at that level below which it is excluded by marine predators or competitors more susceptible to the stresses of emersion. [There are exceptions to this generality, e.g., R. T. Paine (personal communication) finds that the mussel *Mytilus californianus* sets the upper limit of the alga *Alaria marginata*.]

Unlike the semidiurnal tides that predominate throughout the world, the tides in the vicinity of the Aleutian Islands are irregular diurnal (Plate 1 of Doty, 1957), being primarily diurnal but tending toward mixed during neap tides (for definition of terms, see U. S. Department of Commerce, 1949). Figure 2 shows representative tidal curves for March and June 1969 at Amchitka.

The tidal range at Amchitka is narrow compared with those at other locations where descriptive studies of littoral communities have been performed. For example, the diurnal range, the difference between mean higher high water (MHHW) and mean lower low water (MLLW), at South Bight, Amchitka, is 1.1 m, whereas it is 2.5 m at Three Saints Bay, Kodiak Island, Alaska, 2.4 m at Neah Bay, Wash., and 1.6 m (5.2 ft) at Monterey Bay, Calif. (U. S. Department of Commerce, 1969). The maximum tidal range at Amchitka is just over 2 m (2.1 m in 1969 at South Bight). (Computed from hourly tidal height measurements at Sweeper Cove, Adak, Alaska, 1969, which were corrected for Amchitka with the corrections published in the tide tables.)

Temperature and Salinity

McAlister (1971) has discussed several aspects of the offshore marine physical environment in the vicinity of Amchitka. Two aspects of the inshore marine environment, water temperature and salinity, were monitored during the course of our studies.

Water temperature was monitored in Constantine Harbor with 45-day recording thermographs

Fig. 2—Representative tidal curves for March and June 1969. The curves were constructed from hourly tidal height measurements at Sweeper Cove, Adak, Alaska, 1969, obtained from the National Ocean Survey. The hourly tidal heights were corrected for Amchitka with the use of the Constantine Harbor (c) and South Bight (s) corrections published in the tide tables. The corrections are mean values of range and tidal planes computed from automatic tide gauge records. The value for Constantine Harbor on the Bering Sea side of Amchitka is based on a 6-month record by automatic tide gauge, August 1946 through January 1947. The value for South Bight on the Pacific Ocean side is based on a 6-day record by automatic gauge from June 29 to July 5, 1945.

hung approximately 6 m (20 ft) below mean tide level beneath a dock. Figure 3 shows the mean, maximum, and minimum monthly temperature variability for Constantine Harbor based on thermograph data (32 tapes) collected intermittently from 1968 to 1973.

The curve inset in Fig. 3 shows the same water temperature characteristics as the main figure but it is drawn from sea-surface isotherms shown for the vicinity of Amchitka in U. S. Naval Oceanographic Office Publication on Sea Surface Temperatures of the North Pacific Ocean (1969). The curve of mean water temperatures for Constantine Harbor differs very little from that based on Naval Oceanographic Office data except that mean summer temperatures were lower. The position of the thermograph 6 m (20 ft) below the surface may have influenced the readings. Variability in the extreme water temperatures at Constantine Harbor, for the most part, falls within the range for

the U. S. Naval Oceanographic Office data. Surface temperatures of sea water over the intertidal rocky benches show a greater variability than those recorded in Constantine Harbor. Temperatures taken (178) of the water over the bench show a low of 1.1°C in January 1970 at Square Bay and a high of 12.1°C in June 1970 at Makarius Bay.

Samples of surface sea water for salinity analysis were taken in citrate of magnesia bottles concurrently with surface temperature readings at our study sites. Samples were usually taken on an incoming tide at a water level between mean lower low water (MLLW) and mean tide level (MTL). The analysis was done on a laboratory salinometer at the Department of Oceanography, University of Washington. Salinities at the study sites remained, for the most part, between 32 ‰ and 34 ‰. Extremely low salinities were often recorded at Makarius Bay on days with onshore winds. The study site at Makarius Bay is less than 100 m from

Fig. 3.—Water temperatures at Constantine Harbor, Amchitka Island. Records are from 32 recording thermograph tapes taken intermittently from April 1968 through January 1972. Inflections in the curve of means reflect variability resulting from few tapes. Minimum and maximum values are plotted opposite the time of month at which they were recorded. Inset shows the same temperature characteristics based on sea-surface isotherms shown for the vicinity of Amchitka in U. S. Naval Oceanographic Office Special Publication 123.

the mouth of a short stream draining a 10-ha (25-acre) lake (Clevenger Lake). Dye releases at the mouth of the stream indicate that, when onshore winds prevail, much of the stream's effluent is swept south nearshore over the bench.

Climate

The stresses of the physical environment are most severe on marine organisms when they are exposed during low tides. Aspects of the atmospheric climate which are important to these organisms are air temperature, precipitation, insolation, relative humidity, and wind. The following discussion is based on the climatological data of Armstrong (1971; Chap. 4, this volume), who has summarized the surface weather observations of the U. S. Department of the Air Force (Army Air Corps before 1947) at Amchitka during the period February 1943 through June 1948.

As is characteristic of maritime environments, the mean daily and mean annual ranges in air temperature (3.9°C or less and 9.4°C , respectively) are relatively narrow at Amchitka. However, my records from thermographs placed intertidally show that the range in temperature (from submersion to emersion) to which intertidal organisms on Amchitka are exposed during a single tidal cycle

may be as great as the annual range in mean air temperature at Amchitka. Glynn (1965) recorded temperatures in the *Endocladia*–*Balanus* association at Pacific Grove, Calif., for an 8-hr period in September 1961 and found that the range between the highest and lowest of his in situ measurements on exposed rock surface was greater than the range between the mean monthly maximum (September) and minimum (December) air temperature for the year at that locality (see also Hedgpeth and Gonor, 1969).

Severe osmotic stress occurs when emersed intertidal organisms are exposed to heavy rain. However, heavy rains are infrequent at Amchitka; the mean annual precipitation is only 83 cm, and the average number of days with greater than 1 cm precipitation is only 16. Light rain benefits intertidal organisms by reducing desiccation rates.

Other aspects of the maritime climate that promote low rates of desiccation in the intertidal area are a cloudy sky, high relative humidity, and onshore wind. The total frequency of broken and overcast skies at Amchitka is at least 70% every month of the year. Also, heavy cloud cover and fog are most frequent in the summer (90 to 95% and 30 to 52%, respectively) when low tides occur in daylight hours (Armstrong, Chap. 4, this volume).

There is no published summary of relative humidity at Amchitka, but at Shemya Island, 180 miles (290 km) west of Amchitka, the mean monthly relative humidity is 80% or more for all months (U. S. Department of Commerce, 1971).

Winds increase desiccation rates by increasing evaporation; however, onshore winds increase wave splash and sea spray and, if strong enough, may even prevent complete tidal ebbing. Winds from the southwest prevail during the summer; thus desiccation rates of intertidal organisms along the Pacific coast of Amchitka with its southerly aspect are ameliorated during daylight low tides.

Substrate

Powers, Coats, and Nelson (1960) and Gard (Chap. 2, this volume) describe the geology of Amchitka. The general map of the geology of Amchitka in Powers et al. (1960) indicates that the so-called Banjo Point formation, described as "bedded marine sandstone, conglomerate, tuffaceous shale and some lapilli tuff of basaltic composition," forms the substratum of all the study areas to be discussed in this chapter. However, in some areas, especially at Rifle Range Point, the substrate is highly indurated.

METHODS

Transects and Intertidal Arrays

Study Sites. Two intertidal belt transects previously established in March 1968 by F. C. Weinmann at Makarius Bay (T_1) and Square Bay (T_2) for studies of algal ecology were selected as initial benthic invertebrate study sites (Fig. 4). In July 1969 I established a third transect at Rifle Range Point (T_4) (T_4 is not the T_3 of Lebednik and Palmisano, Chap. 17, this volume), and in August 1970 P. A. Lebednik established intertidal arrays (IA-2 and IA-3) of 0.25-m² quadrats on the Bering Sea side of the island. These five study sites provided data on invertebrate distribution and abundance from sheltered and exposed areas on both coasts. On the Pacific Ocean side, T_1 is in a sheltered area and T_4 is an exposed site. On the Bering Sea side, T_2 is sheltered, IA-3 is slightly less sheltered, and IA-2 is exposed. The azimuths and profiles of the transects and the elevations of the plots in the arrays were fixed by standard surveying techniques. All measurements of elevations were subsequently related to mean lower low water (MLLW) for Amchitka by a professional surveying crew. The true azimuth and length of each transect are given in Table 1. In addition to sampling these five main study sites, I made observations of and

collections from over 300 additional plots at these and 12 other intertidal sites (Fig. 4). Most of the time I spent at Amchitka (432 days) was from June to September, but I have made observations there in every month except November.

Sampling Procedures. Each of the three transects was divided along its length into sections on the basis of substrate or dominant algal cover. A minimum of two 0.25-m² plots judged to be typical of each section were selected for sampling. The algal canopy of each plot was photographed and then removed. As the fronds were removed, individuals of each species of invertebrate epifaunal on them were identified and counted. The plot was photographed again. This second photograph was used to determine the percent cover of algal understory and the relative abundance of such invertebrates as *Halichondria panicea*,* an encrusting sponge. The number of individuals of each of the larger macroinvertebrate species was then recorded. This number was combined with the individual counts of species epifaunal on the fronds of the algal canopy. Invertebrates that were too small and too numerous to count over the whole plot were subsampled with a 5-cm (2-in.)-diameter circular ring. Everything within the ring was removed down to bare rock. The number of subsamples taken varied with the heterogeneity of the algal understory and substrate cover. It was sometimes necessary to extrapolate counts of large invertebrates from subsamples of a plot when the plot was threatened with imminent tidal inundation or contained one or two species too numerous to count completely in the time available. Subsamples and representatives of unidentified species were removed to the laboratory where they were fixed in 10% neutral-buffered Formalin. The subsamples were sieved through a 1-mm sieve, sorted, and the animals identified.

Most invertebrates were initially identified from the literature. When possible, representative specimens were compared with museum specimens or sent to specialists for identification or verification (see the appendix).

Transects T_1 and T_2 were sampled in winter, early spring, late spring, summer, and early fall (Table 1). I did not sample the same quadrats on different dates (Figs. 7, 10, and 12 show the locations of quadrat centers sampled on dates other than August–October 1969 at Square Bay). Because of the difficulty of identifying and count-

*The appendix contains a partial list of invertebrates collected at Amchitka including the authority and date of the original description for each scientific name.

Fig. 4—Maps of Amchitka Island showing intertidal collecting areas (⊗, upper map) and major study sites, Cannikin surface zero (⊕) and area of *Chionoecetes bairdi* catches (shaded area, lower map).

ing small invertebrates in situ in the dark in early fall and winter, data from T_1 and T_2 are inadequate for determining seasonal variability in invertebrate abundance. Seasonal data were used only to refine the distributional limits of invertebrates. [If a species was recorded at a position along the transect other than one of those sampled in August–October 1969 (but within the same community) in a different season and there was no a priori reason for not expecting it at that position in August–October 1969, its distribution was extended accordingly.] I found it impossible to continue sampling more than one control when I began the study of the effects of Cannikin (see

below); the transects were abandoned after March 1970.

In August 1970 two intertidal arrays (IA-2 and IA-3) of 0.25-m² quadrats were established by Lebednik (Lebednik and Palmisano, Chap. 17, this volume) on the Bering Sea coast of Amchitka (Fig. 4). Forty quadrats (25 at IA-2 and 15 at IA-3) were placed in patches of more or less uniform algal cover and distributed over the surface of the intertidal bench so that all major algal zones were represented. Each plot was marked in the center and at two corners with flags of polypropylene rope nailed to the bench surface with concrete nails. When data collection on the

Table 1—Azimuths, Lengths (or Size), and Sampling Dates of Three Transects and One Intertidal Grid and Sampling Dates for Two Arrays at Amchitka Island

Study site	Azimuth	Length, m	Sampling dates	Number of plots	
				T ₁	T ₂
Makarius Bay (T ₁)	308°02' True	61.0	{ Aug. 7–10, 1968* Jan. 1–2, 1969 Mar. 24–26, 1969 June 12–15, 1969 Aug. 25 to Oct. 17, 1969 Jan. 3–12, 1970 Mar. 12–16, 1970† July 30 to Aug. 24, 1969	12	14
Square Bay (T ₂)	098°58' True	74.1		3	5
				7	11
				8	8
				16	15
				7	7
Rifle Range Point (T ₄)	179°35' Mag.	78.4	July 30 to Aug. 24, 1969	13	
				IA-2	IA-3
IA-2 and IA-3			Aug. 15–18, 1970	25	6
			Sept. 6–12, 1971	22	15
			Dec. 2–7, 1971	13	6
			Feb. 21–25, 1972	13	7
			Apr. 15–26, 1972	22	13
			June 14–19, 1972	22	13
			Aug. 2–12, 1972	21	12
			Oct. 22–24, 1972	18	12
			Apr. 13–20, 1973	22	12
			Aug. 22 to Sept. 2, 1973	21	11
			May 22–27, 1974	20	12
			Aug. 27–28, 1974	22	12
				Size, m ²	
Makarius Bay intertidal grid	x 192°55' True y 282°55' True	3717.5 (61-m square)	{ Oct. 7–12, 1971 Feb. 20–24, 1972 Aug. 18–22, 1972	12	
				11	
				11	

*Both T₁ and T₂ were visited during each time span through March 1970.

†General observations and physical surveying were done during this period; no plots were sampled.

algae in each quadrat was completed (see Lebednik and Palmisano, Chap. 17, this volume), the number of individuals of the larger macrofaunal invertebrate species (those retained by a 2-mm sieve) were recorded, and the percent coverage of all colonial species within each plot was estimated by visually bisecting the plot into equal-sized rectangles and then subdividing these rectangles into even smaller equal-sized units until an estimate could be gained. It was impossible to obtain consistently accurate counts of individuals of the smaller macrofauna (the majority of whose adults would be retained by a 1-mm sieve) owing to the dense algal cover on most plots, especially in the *Halosaccion*–*Fucus* community. In August 1970 plots that contained almost exclusively these tiny abundant species were subsampled with an 8-cm-diameter, 1.4-cm-deep circular ring in a manner similar to that used to subsample the quadrats on the

transects. However, because of the effect on subsequent observations of sampling without replacement on the same plots, subsampling was stopped after August 1970. Thereafter only semi-quantitative data were collected on small abundant species. Counts of individuals per species were made twice (August 1970 and September 1971) prior to Cannikin. Postevent counts began 1 month after the test and continued on a bimonthly schedule for 10 months. Thereafter counts were made at 17, 22, 30, and 33 months postevent. Rockfalls due to Cannikin buried seven plots (five at IA-2 and two at IA-3). So that the loss of these plots could be compensated for, two stations were added at IA-2 in February 1972. Table 1 gives sampling dates and the number of plots sampled for each date for IA-2 and IA-3. An intertidal grid established at Makarius Bay for another study acted as the control.

Intertidal Grid

A stratified random sampling scheme with major algal zones as strata was adopted for sampling populations of invertebrates at Makarius Bay. A 200-ft(61-m)-square grid was laid out with standard surveying equipment to fix the azimuths of the axes. Each axis was then divided along its length into 10-ft (3.1-m) intervals, each of which was marked with a flag of polypropylene rope or surveyor's flagging nailed to the bench surface with a concrete nail and washer. These markers facilitated the procedure for mapping the major algal zones within the grids and helped in locating the positions of the plots to be sampled.

Mapping of Algal Zones. The procedure for mapping the major algal zones was as follows: A surveyor's tape was stretched out the width of the grid in a direction perpendicular to one of the grid axes from one of the marked points along the axis. The algal zone within which the tape intersected the axis was recorded. I then walked along the tape and recorded the sequence and widths of the major algal zones where they were intersected by the tape. The tape was stretched tight before each measurement was taken. This procedure was repeated for the remainder of the marked points along the same axis and all the points along the perpendicular axis. Forty runs were made on the grid. The runs were reproduced to scale on graph paper as lines whose segments represented segments of the surveyor's tape which passed over a particular algal zone. By connecting the points that marked the boundaries of the algal zones along the line segments, I obtained a map of the distribution of the major algal zones within the grid. When there was doubt about the position of the boundaries, as in areas of irregular topography where algal zones changed rapidly and irregularly, the map was compared directly with the algal distribution in the field.

The algal map was used to determine the allocation of sample size within strata (algal zones). After the map had been drawn up, the relative areas of each algal zone within the grid were determined with a compensating polar planimeter. The number of quadrats allotted to each stratum was proportional to the relative area of that stratum in the grid.

The coordinates of each plot were taken from a random-number table and plotted on the map of the grid. The numbers taken from the table represented distances (in meters) from the grid origin along the axes. Coordinates were taken in this manner until the sample size quota for all the

algal zones was met. If the quota of one algal zone was filled before the others, coordinates that subsequently fell in that zone were ignored.

Quadrats were positioned in the field by measuring the distance of one coordinate along one axis (usually that axis parallel to the shore) and then stretching a surveyor's tape in a perpendicular direction to a length equal to the other coordinate. Perpendicularity was determined with a Brunton pocket transit. The length on the surveyor's tape corresponding to the second coordinate marked the center of the quadrat to be sampled.

Quadrats with a surface area of $\frac{1}{16}$ m² were used to sample the grid. As each quadrat was positioned, a photograph was taken to record the percent cover of the canopy-forming algae. The fronds of these algae falling within the quadrat were then removed and placed in a polyethylene bag, and the plot was rephotographed to record the percent cover of understory algae, holdfasts of canopy algae, and colonial invertebrates, such as encrusting sponges. The plot was then stripped to bare rock with paint scrapers, stone chisels, and modified spoons, the contents were placed in the polyethylene bag with the canopy algal fronds, and the bag was labeled. The plot was then marked at one corner with a concrete nail, washer, and surveyor's flagging for future reference. When all plots had been sampled in each season, their elevations were related (using standard surveying techniques) to points whose elevations were determined by a professional surveying crew. The samples were removed to the laboratory for processing. Time did not permit full processing of the samples at the field station; so most samples were fixed in 10% neutral-buffered Formalin and shipped to Seattle. Makarius Bay was sampled in the fall 1 month prior to Cannikin and in late winter and late summer following Cannikin (Table 1). No obvious changes (i.e., no uplifting) had occurred on the grid after Cannikin, and therefore it was not remapped.

Each sample was screened successively through standard screens with mesh openings of 4, 2, and 0.991 mm and the invertebrates were separated for species abundance counts. All invertebrates were counted and preserved in 70% isopropyl alcohol containing 2% glycerin. Invertebrates retained by the 0.991-mm screen were counted under a dissecting microscope. Invertebrates of the major taxonomic groups Mollusca, Echinodermata, and Crustacea, excluding Amphipoda, were identified to species, and the individuals of each of these species were counted. Invertebrates of minor phyla were identified to species when possible.

Sources of Bias and Error. The grid at Makarius Bay was established primarily to act as a control for another study. Because the sample surfaces ($\frac{1}{16}$ m² versus $\frac{1}{4}$ m²) and the sampling schemes for Makarius Bay and IA-2 and IA-3, respectively, were different, the Makarius Bay grid was not a proper control for the plots at IA-2 and IA-3. However, limits on field time and resources precluded the maintenance of two controls. In view of the striking changes that occurred at IA-2 and IA-3 following Cannikin, the results would probably not have been different had an additional control been added at Makarius Bay using a sampling scheme and sample surface identical to that at IA-2 and IA-3. Both sample surfaces and associated data-collection procedures were used at Makarius Bay, and those used on the intertidal grid always turned up more species and individuals in a given plot despite the reduced sample surface and would be expected to be at least as sensitive to changes in species abundance patterns as that used at IA-2 and IA-3 even with the introduced spatial variability in abundances due to random sampling.

Other sources of error are as follows:

1. The abundances of certain highly motile forms, e.g., gammarids, capable of withdrawing deeply into the holdfast systems of algae when emersed or of escaping unnoticed from quadrats during sampling were probably often underestimated as compared with the less active species with the use of both of the sampling schemes described above.

2. The abundances of the smaller forms of both the large (retained by a 2-mm or larger mesh screen) and small (retained only by a 1-mm screen) size classes were probably underestimated as compared with the larger forms, depending on the sampling procedure.

3. Small species about the same size may be under- or overrepresented because different growth forms have different probabilities of retention by the sieves.

4. Since invertebrates were assigned to communities on the basis of their distributions as determined by sampling of emersed populations, we do not have a completely accurate picture of the composition of these communities or of the spatial relationships between species when the communities are immersed and fully functioning. Nevertheless, although the spatial relationships of the motile invertebrates may change slightly with the tide, extensive vertical migrations are precluded by the essentially horizontal nature of the intertidal benches. Moreover, the dense cover of macroscopic algae probably reduces the stresses associated with

emersion and thus reduces the necessity for organisms to move to lower levels with the receding tide. The spatial relationships among sessile organisms, such as barnacles, of course, do not change with the tide.

5. Because of the dense algal cover on the IA-2 and IA-3 plots prior to Cannikin, it was often difficult to get complete counts of even the larger macrofauna. As the algal cover died and sloughed off, blew away, or was washed away in storm waves after Cannikin, invertebrates became much easier to see, and species counts could be made easily. Therefore the probability of underestimating the preshot abundances of species in the IA-2 and IA-3 plots was much greater than that for the postshot counts.

Three sources of error may have affected my zoogeographic analyses. The first results from the tendency of early taxonomists to describe more species than are valid. Thus some species of mollusks described by Dall from the Aleutians may prove to be synonymous with previously described forms as have, for example, some of the tellinids he described (Coan, 1971). This type of error would bias my zoogeographic analysis by erroneously inflating the number of endemic species.

A second and opposite source of error results from the tendency of students newly initiated to a fauna to force their specimens into existing keys, thereby missing new species and wrongly assigning specimens to more widely distributed species. I have made every effort to have my identifications verified by specialists (see the appendix), therefore the above sources of error are probably negligible.

Another source of error results from an incomplete knowledge of the distributions of some species. Because of the relative inaccessibility of the Russian and Japanese literature, my determination of the relative contributions of Asiatic and North American faunas to the benthic invertebrate fauna of Amchitka may be biased. The recent papers of Spassky (1961) and Golikov and Kussakin (1962), which include extensive lists of invertebrates occurring on the shores of Kamchatka and the Kurile Islands, help reduce the magnitude of this source of error.

RESULTS AND DISCUSSION

Intertidal Communities

Assemblages of marine intertidal species have been treated traditionally as "random aggregations of species sharing similar physical tolerances" (Dayton, 1971). This viewpoint particularly characterizes the literature on intertidal zonation (see

reviews by Lewis, 1964; Ricketts, Calvin, and Hedgpeth, 1968; Stephenson and Stephenson, 1972), yet recent studies have demonstrated conclusively that these aggregations of species are indeed organized systems of species, i.e., communities, whose structure is based on dynamic interactions, including competition and predation (Connell, 1961a; 1961b; 1970; Paine, 1966; 1974; Dayton, 1971; 1975).

The definition of community used here is an operational one: "a group of species which are often found living together" (Fager, 1963). Communities are designated following the dominance—constancy school (Stephenson, 1973) with algae as characterizing species. Under this school identification of communities is subjective, and boundaries between communities are frequently artificial; subdominants (in this case invertebrates) often do not conform to the distributional patterns of dominants (Stephenson, 1973). This system of community classification is used here for the following three reasons:

1. Marine intertidal communities can be observed directly, although observation usually takes place when species are emersed and less active and fewer interactions are occurring. Still, not all species interactions in the intertidal area cease at low tide, and the spatial relationships between most species probably do not change drastically whether the community is immersed or emersed. Since these communities can be observed directly, numerical classification (Stephenson, 1973) is unnecessary.

2. The dominance—constancy school is particularly applicable to Amchitka because, depending on tidal level, exposure, and shore topography, one or another dominant algal species essentially forms a pure stand (see Lebednik and Palmisano, Chap. 17, this volume).

3. Our knowledge of the interactions structuring marine invertebrate communities at Amchitka is meager; species known to play important roles in structuring rocky intertidal communities elsewhere in the North Pacific (Paine, 1966; 1974; Connell, 1970; Dayton, 1971) are either absent or in low abundance. We simply do not know enough about the species interactions at Amchitka to base our designation of invertebrate communities on them.

The following rocky intertidal communities were identified: (1) the *Laminaria* community, (2) the *Alaria-Hedophyllum* community, and (3) the *Halosaccion-Fucus* community. All these communities are within the region of the midlittoral and sublittoral fringe zones of Stephenson and Stephenson's (1949) universal scheme. The supralittoral fringe was not sampled quantitatively at

any of the five main study sites, although species characteristic of it are listed in the appendix.

Drift-kelp windrows are also a conspicuous feature on the shore at Amchitka. These are made up chiefly of reducer and decomposer organisms, including the amphipod (*Orchestia* sp.), coeloplid flies, and nematodes (Chew, 1969). Judging from the great biomass of dead and dying algae periodically washed ashore and the high rate at which it is broken down, these windrows probably contribute a great deal to the productivity of the neritic and nearshore benthic environment in the form of dissolved organic matter, detritus, and food organisms. My observations and those of others indicate that these drift-kelp windrows provide an important food resource for the Norway rat (*Rattus norvegicus*) and probably also seasonally important to several species of birds, e.g., Winter Wrens (*Troglodytes troglodytes*), Rock Sandpipers (*Calidris ptilocnemis*), and Ruddy Turnstones (*Arenaria interpres*).

Where do invertebrates fit in this scheme of communities? Species that characterize a particular community should show high fidelity for that community (i.e., occur there more frequently than in other communities) and show a high constancy, or frequency, in that community (i.e., occur in a large proportion of the samples from that community) (Fager, 1963). Invertebrates were "assigned" to that community to which they were most faithful. Fidelity (f) was measured as the proportion of quadrats containing the species that was in a particular community. A species was considered to be faithful to a particular community if one-half or more of the quadrats containing the species were in that community. Constancy (c) was measured as the proportion of quadrats from a particular community that contained the species.

Species in each community were ranked on fidelity and constancy (1, lowest rank for both categories). Large species were ranked separately from small species. An average of the ranks ($\bar{R}$) of these two statistics for each species was then calculated after the ranks were corrected, if necessary, for inequality in the highest ranks; so fidelity and constancy have equal weight in the rank ($\bar{R}$) of each species. Species were then listed in order of decreasing $\bar{R}$. Species with equal $\bar{R}$ were listed in order of decreasing abundance. Species with the highest ranks ($\bar{R}$) (five large species and five small species) were then selected as characteristic of each community.

***Laminaria* Community.** The *Laminaria* community has its greatest development at the seaward edges of the intertidal benches; it is also found in channels that cut the benches, but its upper limit is

lowered as one progresses shoreward, where it may be completely replaced by the *Alaria-Hedophyllum* community. The *Laminaria* community is dominated by *Laminaria longipes* at all degrees of exposure. It ranges from -3 or -5 m (Lebednik and Palmisano, Chap. 17, this volume) to as high as +0.61 m in exposed situations.

Of the 142 species of invertebrates (excluding those not identified to species) found at the five main study sites, 110 were found in the *Laminaria* community. The average number of species per 0.25 m² among the large species was also greater in the *Laminaria* community (13 species) than in the next richest community (*Alaria-Hedophyllum*, 11 species). Considering data from transects T₂ and T₄ only and including small species, the difference between these two communities is more pronounced (42 vs. 32 species per sample). The number of species that were faithful (*f* greater than 0.5) to the *Laminaria* community (73 species) far exceeded that for the other two communities (19 species and 17 species for the *Alaria-Hedophyllum* and *Halosaccion-Fucus* communities, respectively).

Within the *Laminaria* community species counts were greatest among the Polychaeta (30 species) and the Gammaridea and Gastropoda (19 species each). Figures 5 and 6 show the distributions and relative abundances of species in the *Laminaria* community for two transects representative of an exposed location [Rifle Range Point (T₄)] (Fig. 7) and a sheltered one [Square Bay (T₂)] (Fig. 8).

The ten most characteristic invertebrates of the *Laminaria* community are listed in Table 2 along with several statistics suggestive of their role in community structure (see Fager, 1963). Species are listed in order of decreasing mean rank ($\bar{R}$) for each size class (large-size class on top). They include a sponge, four polychaetes, two echinoderms, two gastropods, and an amphipod.

Other species among the large-size class with large rank ($\bar{R}$) included *Ophiopholis aculeata* (10.5), *Henricia leviuscula* (10.5), *Aleutiaster schefferi* (10), *Natica clausa* (9.5), and *Halichondria panicea* (8). The first four species showed high fidelity for the *Laminaria* community (*f* = 1.0, 1.0, 0.72, and 0.86, respectively), but they were rare. The sponge *Halichondria panicea* showed a high constancy (*c* = 10/15) for the *Laminaria* community, but it also occurred frequently in the *Alaria-Hedophyllum* community; therefore *f* was small (0.53).

Three of the large-size-class species in Table 2 (*Strongylocentrotus polyacanthus*, *Notoacmea scutum*, and *Leptasterias aleutica*) had comparable abundances and did not differ greatly in average

rank ($\bar{R}$, see Table 2 for a definition of this statistic) or dominance. *Mitrella amiantis* by contrast was clearly more abundant and had a higher average rank and greater dominance than the other three species. However, because *M. amiantis* is much smaller than an average individual of the above species, it is clearly not dominant in biomass. Statistics based on abundance were not calculated for the sponge *Scypha compressa* because abundance was measured as percent cover, not numbers of individuals.

The assignment of characteristic species status to the five species of the small-size class is tentative because the number of plots sampled for the small species in the *Laminaria* community (3) is extremely small. Three species, *Demonax* sp., *Autolytus beringianus*, and *Cercops compactus*, were found in only one sample, but that sample occurred in the *Laminaria* community, making their fidelity 1.0; so their rank ($\bar{R}$) was consequently high. Several other species, including *Balcis randolphi*, *Syllis (Typosyllis)* sp., and *Dexiospira* sp., occurred frequently in the *Laminaria* community at Makarius Bay and IA-2, but data from these two localities are not complete for all species and were not included in the calculations for the small species. If these data are considered, *Balcis*, especially, shows both high constancy in (0.73) and high fidelity for (0.80) the *Laminaria* community.

The sea urchin *Strongylocentrotus polyacanthus* has potentially the most important role in structuring the *Laminaria* community of all the invertebrates found there. Descriptive-comparative studies (Estes and Palmisano, 1974; Chap. 22, this volume) of islands with low (Amchitka and Adak) and high (Shemya and Attu) urchin biomass indicate that this species can have a profound effect on populations of lower intertidal and shallow subtidal algae and probably other invertebrates as well. These authors argue that overexploitation of urchins by sea otters (*Enhydra lutris*) reduces considerably the impact of the sea urchin at Amchitka. They contend that, in the presence of otter predation, urchin individual size and population biomass are reduced, permitting benthic algae and associated invertebrates to flourish.

Other species that may be important to the structure of the *Laminaria* community are the starfish *Leptasterias alaskensis* and *L. aleutica* (see taxonomic note in the appendix). Preliminary feeding observations on these species in the field indicate that they are generalist predators that feed mostly on gastropods and peracaridan crustaceans (personal observations; Palmisano, 1975). These two species were not distinguished during these

Fig. 5—Distributions and abundances of species that were most abundant in the *Laminaria* community at Rifle Range Point (T_4), Amchitka Island, in August 1969. Abundances are numbers of individuals per 0.25 m^2 except as noted. *, Estimates based on two or more subsamples of 19.6 cm^2 . †, Scale is in units of percent cover.

Fig. 6. --Distributions and abundances of species that were most abundant in the *Laminaria* community at Square Bay (T₂), Amchitka Island, in August and September 1969. Abundances are numbers of individuals per 0.25 m² except as noted. Centers of quadrats sampled on dates other than August and September 1969 are shown below the quadrat numbers of August and September 1969. *, Estimates based on two or more subsamples of 19.6 cm². †, Scale is in units of percent cover. ‡, Presence data only.

Fig. 7—Rifle Range Point transect (T_4). (Photograph taken by C. A. Simenstad in May 1974.)

feeding observations, so we do not know how their diets differ. Our observations are scanty, but neither species appears to feed on barnacles as does the closely related *L. hexactis* (Mauzey, Birkeland, and Dayton, 1968; Menge, 1972). Presumably this is because of the low abundance of *Balanus glandula* and *B. cariosus* at Amchitka.

A fourth species that may be an important occupier of space is *Halichondria panicea*, because of its encrusting growth form, potentially large size (mean and range of percent cover were 12.6%, 1 to 55% for all those 0.25-m² quadrats in which it was found), and relative commonness in the lower intertidal area (c. 33/60). Interactions involving *Halichondria* include possible predation on it by the starfish *Henricia tumida* and parasitism by the snail *Cerithiopsis stejnegeri*. *Henricia* has been seen pressed against *H. panicea*; when the starfish was removed, the sponge tissue beneath it was found to be discolored. Mauzey et al. (1968) discuss the possibility that another North Pacific congener, *H. leviuscula*, may also prey on encrusting sponges.

Cerithiopsis stejnegeri was rare at the five main study sites, but, because of its small size, it can be easily overlooked in the field. Since it was rare it did not show high affinity with *Halichondria*. However, *C. stejnegeri* was found only in quadrats containing *H. panicea*; when seen in the field, the snail was almost invariably on or under the sponge. Another North Pacific snail, *C. stephensae*, has been observed in association with *H. panicea* (Bakus, 1966). In the British Isles *C. tubercularis* is known to eat *Halichondria* and other sponges (Fretter, 1951).

***Alaria Hedophyllum* Community.** The *Alaria Hedophyllum* community ranged in vertical distribution from -53.4 to +9.1 cm (-21 to +3.6 in.) in extreme shelter (transect T_1) to 0 to +160.1 cm (0 to 63 in.) in extreme exposure (transect T_4). *Hedophyllum sessile* usually dominates this community in sheltered situations, but, as exposure increases, *Alaria crista* becomes dominant (Lebednik and Palmisano, Chap. 17, this volume). In exposed localities *Hedophyllum* is

Fig. 8—Square Bay transect (T_2). (Photograph taken by Charles E. O'Clair on May 26, 1974.)

usually absent except well back from the seaward edge of the benches in depressions, tide pools, and drainage channels (Fig. 9). *Alaria* can be found in patches at Makarius Bay, the most sheltered locality studied (see Lebednik and Palmisano, Chap. 17, this volume).

Despite the fact that the species of algae dominating this community changed with the degree of exposure, invertebrate species composition was similar regardless of which species of algae dominated. Only two species of invertebrate present in more than one quadrat were restricted to the *Hedophyllum*-dominated quadrats, and none were restricted to *Alaria*-dominated quadrats. If differences in the relative abundances of species of invertebrates between *Hedophyllum*-dominated quadrats and *Alaria*-dominated quadrats are considered, there does appear to be an increase in the abundances of certain suspension-feeding species, such as mussels, *Mytilus edulis*, and barnacles,

Balanus cariosus, with increasing exposure and therefore with increasing dominance of *Alaria*. However, these differences did not justify the establishment of two separate communities, one dominated by *Hedophyllum* and one dominated by *Alaria*.

The total species count in the *Alaria*–*Hedophyllum* community was great (114 species), but few species (19) were faithful to it. As in the *Laminaria* community, species counts were greatest among the Polychaeta (35 species), followed by Gastropoda (23 species) and Gammaridea (18 species). The distributions and relative abundances of species in the *Alaria*–*Hedophyllum* community are shown in Figs. 9 and 10 for representative localities, T_4 and T_2 , respectively.

Table 3 shows the ten most characteristic invertebrates of the *Alaria*–*Hedophyllum* community and their statistics. This table contains all the

Table 2—Statistics for the Five Most Characteristic Species of Invertebrates of Two Size Classes from the *Laminaria* Community*

Species	Taxon†	Fidelity (f.)‡	Constancy (c.)§	$\bar{R}\parallel$	Abundance**	Average rank ($\bar{r}$)††	Dominance‡‡	Dispersion§§	Vitality
Larger Species Counted in 0.25-m ² Quadrats									
<i>Strongylocentrotus polyacanthus</i> ¶¶	E	0.84	10/15	16	2, 1-10 (1, 1-10)	1.4	1/15	$\hat{K}_1 = 0.6$ Aggregated	Sizes up to 30-mm test diameter present.
<i>Mitrella amiantis</i>	G	0.73	13/15	15	12, 1-124 (16, 1-49)	4.8	7/15	$\hat{K}_1 = 1.2$ Aggregated	All stages present.
<i>Notoacmea scutum</i>	G	0.92	6/15	14	1, 1-2 (1, 1-2)	0.47	0/15	Random	Present year round.
<i>Scypha compressa</i>	P	0.78	9/15	13.5	2.5%, 1-5% (3.2%, 1-9%)				Present year round.
<i>Leptasterias aleutica</i> ***	A	0.62	13/15	12.5	3.2, 1-21 (2.5, 1-9)	2.73	2/15	$\hat{K}_1 = 2.4$ Slightly aggregated	Juvenile and adult stages present.
Small Species Whose Abundances Were Estimated from 50-mm-Diameter Subsamples of Quadrats									
<i>Lumbrineris inflata</i>	Pc	0.89	2/3	7	69, 38-90 (80, 69-90)	8.3	1/3	$\hat{K}_1 = 1.2$ Aggregated	Adults present.
<i>Caulerella alata maculata</i>	Pc	0.80	2/3	6	38, 1-167 (38, 23-54)	7.0	1/3	$\hat{K}_1 = 0.9$ Aggregated	Adults present.
<i>Demonax</i> sp.	Pc	1.0	1/3	6	6	1.33	0/3	$\hat{K}_1 = 0.4$ Aggregated	Adults present.
<i>Autolytus beringianus</i>	Pc	1.0	1/3	6	2	0.67	0/3	$\hat{K}_1 = 0.68$ Aggregated	Adults present.
<i>Cercops compactus</i>	C	1.0	1/3	6	1	0.33	0/3	Random	Adults present.

*Format modified after Table 2 of Fager and McGowan (1963).

†A, Asteroidea; E, Echinoidea; C, Caprellidea; G, Gastropoda; P, Porifera; Pc, Polychaeta.

‡Proportion of quadrats containing the species that was in this community corrected for differences in sample size between communities.

§Proportion of quadrats from this community that contained the species.

¶Average of ranks of fidelity and constancy for each species.

**Median and range of numbers of individuals per 0.25 m² in all quadrats in which the species was found and (in parentheses) these same statistics for quadrats from this community in which the species was found. Abundance of *S. compressa* is the mean and range of percent cover per quadrat; other statistics based on abundance are not included for *Scypha*.††Ranks for each species were averaged over 15 (large species) and 3 (small species) quadrats. The average ranks of the most abundant large and small species in the *Laminaria* quadrats were 6.53 and 12.66, respectively (1, least abundant).

‡‡Proportion of quadrats from this community in which the species was among those making up 50% of the individuals. Summation in each quadrat began with the most abundant species.

§§ $\hat{K}_1$, the first approximation of the exponent K of the negative binomial distribution. Overdispersion increases as K goes to 0. Dispersion was judged random if the quotient of the sample variance divided by the sample mean was not significantly different from one; the relation $\chi^2 = ns^2/\bar{X}$ was used for tests of significance.¶¶See taxonomic note under *S. polyacanthus* in appendix.***See taxonomic note under *L. aleutica* in appendix.

large species that are faithful to this community and slightly more than one-third of the small species owing to the small number of faithful species.

Species that we might predict to have important roles (as successful competitors for space) in structuring the *Alaria-Hedophyllum* community are *Mytilus edulis* and *Balanus cariosus*, although this proved not to be true at Amchitka. *Mytilus edulis* is a widely distributed species in north temperate and subarctic regions and forms conspicuous belts in the midlittoral zone (Stephenson and

Stephenson, 1972), frequently to the exclusion of other species, such as barnacles and limpets (Lewis, 1964, p. 95). Whether *M. edulis* competitively excludes these species has yet to be demonstrated. *Mytilus californianus* has been shown to displace other upper intertidal species when it is released from predation by experimental removal of its primary predator, the starfish, *Pisaster ochraceus* (Paine, 1966; 1974). For at least one species, *Anthopleura elegantissima*, Paine has observed competitive exclusion by *Mytilus californianus* (see Dayton, 1971).

Fig. 9—Distributions and abundances of species that were most abundant in the *Alaria*–*Hedophyllum* community at Rifle Range Point (T_4), Amchitka Island, in August 1969. Abundances are numbers of individuals per 0.25 m^2 except as noted. *, Estimates based on two or more subsamples of 19.6 cm^2 . †, Scale is in units of percent cover. ‡, Specimens incomplete and unidentifiable. §, Presence data only.

Fig. 10—Distributions and abundances of species that were most abundant in the *Alaria*–*Hedophyllum* community at Square Bay (T₂), Amchitka Island, in August and September 1969. Abundances are numbers of individuals per 0.25 m² except as noted. Centers of quadrats sampled on dates other than August and September 1969 are shown below the quadrat numbers of August and September 1969. *, Estimates based on two or more subsamples of 19.6 cm². †, Scale is in units of percent cover.

Table 3—Statistics for the Five Most Characteristic Species of Invertebrates of Two Size Classes from the *Alaria-Hedophyllum* Community*

Species	Taxon†	Fidelity (f.)‡	Constancy (c.)§	R¶	Abundance**	Average rank (r)††	Dominance‡‡	Dispersion§§	Vitality
Larger Species Counted in 0.25-m ² Quadrats									
<i>Mytilus edulis</i>	B	0.7	6/44	3.5	4, 1-40 (5, 1-40)	0.50	1/44	$\hat{K}_1 = 0.66$ Strongly aggregated	Present year round.
<i>Balanus cariosus</i>	Ci	0.67	10/44	3.5	4, 1-24 (4, 1-24)	0.65	1/44	$\hat{K}_1 = 0.1$ Strongly aggregated	Present year round. All benthic stages present.
<i>Katharina tunicata</i>	Am	1.0	2/44	2.5	1 (1)	0.04	0/44	Random	Juveniles and adults present.
<i>Macoma calcaria</i>	B	0.66	3/44	2.0	2, 1-3 (1, 1-2)	0.07	0/44	$\hat{K}_1 = 0.2$ Strongly aggregated	Juveniles present.
<i>Anisogammarus confervicolus</i>	Ga	0.57	3/44	1.5	11, 1-26 (3, 1-4)	0.18	0/44	$\hat{K}_1 = 0.08$ Strongly aggregated	Juveniles and adults present.
Small Species Whose Abundances Were Estimated from 50-mm-Diameter Subsamples of Quadrats									
<i>Corophium brevis</i>	Ga	0.62	5/12	3.5	412, 1-3937 (190, 1-2201)	2.92	0/12	$\hat{K}_1 = 0.16$ Strongly aggregated	All stages present.
<i>Cerithiopsis stejnegeri</i>	G	1.0	2/12	3.5	6, 1-11 (6, 1-11)	0.33	0/12	$\hat{K}_1 = 0.1$ Strongly aggregated	Juveniles and adults present.
<i>Lumbricillus</i> sp.	O	0.57	12/12	3	328, 11-2661 (372, 100-1698)	9.67	1/12	$\hat{K}_1 = 1.3$ Aggregated	Juveniles and adults present.
<i>Vitrinella</i> sp.	G	1.0	1/12	3	64 (64)	0.25	0/12	$\hat{K}_1 = 0.08$ Strongly aggregated	Adults present.
<i>Sphaerosyllis</i> sp.B	Pc	0.66	2/12	3	54, 1-64 (59, 54-64)	1.08	0/12	$\hat{K}_1 = 0.2$ Strongly aggregated	Immature stages present.

*Format modified after Table 2 of Fager and McGowan (1963).

†Am, Amphineura; B, Bivalvia; Ci, Cirripedia; G, Gastropoda; Ga, Gammaridea; O, Oligochaeta; Pc, Polychaeta.

‡Proportion of quadrats containing the species that was in this community corrected for differences in sample size between communities.

§Proportion of quadrats from this community that contained the species.

¶Average of ranks of fidelity and constancy for each species.

**Median and range of numbers of individuals per 0.25 m² in all quadrats in which the species was found and (in parentheses) these same statistics for quadrats from this community in which the species was found.††Ranks for each species were averaged over 44 (large species) and 12 (small species) quadrats. The average ranks of the most abundant large and small species in the *Alaria-Hedophyllum* quadrats were 7.02 and 13.67, respectively (1, least abundant).

‡‡Proportion of quadrats from this community in which the species was among those making up 50% of the individuals. Summation in each quadrat began with the most abundant species.

§§ $\hat{K}_1$, the first approximation of the exponent K of the negative binomial distribution. Overdispersion increases as K goes to 0. Dispersion was judged random if the quotient of the sample variance divided by the sample mean was not significantly different from one; the relation $\chi^2 = ns^2/\bar{X}$ was used for tests of significance.

At Amchitka small to large (from about 15 mm to about 40 mm* in shell length) *M. edulis* showed a high fidelity for the *Alaria-Hedophyllum* community but occurred there relatively infrequently and in low abundance. Its low numerical domi-

nance is not suggestive of a successful monopolizer of space. However, very small individuals of *Mytilus* were found to be quite numerous (see discussion of *Halosaccion-Fucus* community).

Dayton (1971) has shown that, in the absence of predation by the snails, *Thais* spp., and the starfish, *Pisaster ochraceus*, and of disturbance by limpets, *Collisella* spp., *Balanus cariosus* competitively excludes other species of barnacles and

*Shell length was measured from beak to posterior edge of shell.

dominates space in the lower middle intertidal area. Indeed, *B. cariosus* may escape the effects of limpets and *Thais* and eventually occupy 100% of the space if the probability of being removed by drift logs is low.

Pisaster is absent from Amchitka, and only the sea otter is close to the starfish's ecological equivalent. Kenyon (1969) reports on the examination of stomachs from 475 otters killed at Amchitka in 1962 and 1963. *Balanus cariosus* was not reported from any of them. However, Barabash-Nikiforov (1947) found that *B. cariosus* remains were occasionally present in sea otter feces, and sea otters have been seen feeding on *B. cariosus* in the Aleutians (J. F. Palmisano, personal communication). The population statistics for *B. cariosus* indicate that it is uncommon, low in abundance, and rarely numerically dominant at Amchitka (Table 3). Yet at Shemya Island, approximately 180 miles (300 km) to the west, *B. cariosus* is more frequent (60% of *Alaria-Hedophyllum* plots) and more abundant (median abundance, 17; range 1 to 77) per $\frac{1}{16}$ m² and forms a conspicuous belt in the lower middle intertidal area. Considering the data of Kenyon (1969) and Barabash-Nikiforov (1947) on the diet of sea otters, it is unlikely that *B. cariosus* populations are directly limited by sea otter predation on Amchitka. However, the difference in densities of *B. cariosus* on Amchitka and Shemya suggests that *B. cariosus* populations on Amchitka may be affected indirectly by otter predation (Palmisano and Estes, Chap. 22, this volume).

Halosaccion-Fucus Community. The *Halosaccion-Fucus* community ranges in vertical distribution from -21 to +76 cm (-8.3 to +30 in.) in sheltered localities and about +30 cm to at least +174 cm (+69 in.) in exposed localities. *Fucus distichus* dominates this community on igneous boulders and rock fragments in channels or on erosion-resistant knobs projecting above the bench (Lebednik and Palmisano, Chap. 17, this volume), whereas *Halosaccion glandiforme* usually dominates the benchflat. However, mixed stands of *Halosaccion*, *Fucus*, and a third alga, *Iridaea cornucopiae*, are common on the shoreward and upper levels of the benches.

The *Halosaccion-Fucus* community had the lowest species count (91 species) of all three communities. The average species count per 0.25 m² was also low (large species, 8; including small species, 11). Seventeen species (8 large and 9 small) were faithful to the *Halosaccion-Fucus* community. Within the *Halosaccion-Fucus* community, species counts were greatest among the Polychaeta (24 species), followed by the Gas-

tropoda (20 species) and the Gammaridea (15 species). The distributions and relative abundances of species in the *Halosaccion-Fucus* community are shown in Figs. 11 and 12 for Rifle Range Point and Square Bay, respectively.

Table 4 shows ten characteristic invertebrates of the *Halosaccion-Fucus* community and their statistics. All the large species are herbivorous gastropods. Two other species, *Balanus glandula* and *Collisella strigatella*, had the same rank (R) as *Littorina aleutica*, but their median abundances were less.

Balanus glandula ranges from the Aleutian Islands to Ensenada, Baja Calif., and is normally one of the most abundant animals in the upper intertidal area (Ricketts et al., 1968), forming along with other barnacles a distinct zone (Stephenson and Stephenson, 1972). Yet, at the five main study sites on Amchitka, the median [I use the median here; it is a better statistic of location than is the mean when species have clumped distributions (e.g., Fager, 1963)] number of individuals of *B. glandula* per 0.25 m² in quadrats in which it was found was very low (3), much lower than the median number of individuals (235 per 400 cm² = 1470 per 0.25 m²) reported by Glynn (1965, Table XXIV) for Monterey Bay, Calif. Glynn, however, selected his quadrat sites where *Endocladia muricata* and *B. glandula* dominated, and therefore the median number of individuals of *B. glandula* would be expected to be high. Nybakken (1969) reports an abundance of 16.18 (mean number of individuals in 0.25-m² plots containing the species) for *B. glandula* at Three Saints Bay, Kodiak Island, Alaska, which is lower than that for Amchitka (143 per 0.25 m²) (Nybakken did not report the median number of *B. glandula* per 0.25 m² in his study areas), but the relatively high mean recorded at Amchitka is due to an individual count of 1760 in one quadrat. If that count is excluded, the mean drops to 8.5. Moreover, the low abundance recorded for *B. glandula* by Nybakken may be a result of competitive exclusion by the competitive dominant *B. cariosus*. Nybakken reports that *B. cariosus* dominated the barnacle zone at the site where *B. glandula* abundance was estimated. Nowhere on Amchitka does *B. glandula* have densities as high as those recorded in Puget Sound, Wash. (Shelford et al., 1935), the outer coast of Washington (Dayton, 1971), and Monterey Bay, Calif. (Glynn, 1965); yet at Shemya Island my counts have been as high as 2532 per 0.062 m².

Most of the area of the intertidal rock bench at Amchitka is below the optimal tidal height for *B. glandula*. My sampling was restricted to these

Fig. 11.—Distributions and abundances of species that were most abundant in the *Halosaccion-Fucus* community at Rifle Range Point (T₄), Amchitka Island, in August 1969. Abundances are numbers of individuals per 0.25 m² except as noted. *, Estimates based on two or more subsamples of 19.6 cm².

Fig. 12.—Distributions and abundances of species that were most abundant in the *Halosaccion-Fucus* community at Square Bay (T_2), Amchitka Island, in August and September 1969. Abundances are numbers of individuals per 0.25 m^2 except as noted. Centers of quadrats sampled on dates other than August and September 1969 are shown below the quadrat numbers of August and September 1969. *, Estimates based on two or more subsamples of 19.6 cm^2 .

Table 4—Statistics for the Five Most Characteristic Species of Invertebrates of Two Size Classes from the *Halosaccion*–*Fucus* Community*

Species	Taxon†	Fidelity (f.)‡	Constancy (c.)§	$\bar{R}\P$	Abundance**	Average rank (r)††	Dominance‡‡	Dispersion§§	Vitality
Larger Species Counted in 0.25-m ² Quadrats									
<i>Littorina atkana</i>	G	0.67	41/53	6.5	6, 1-844 (6, 1-844)	2.79	11/53	$\hat{K}_1 = 0.1$ Strongly aggregated	Present year round.
<i>Siphonaria thersites</i>	G	0.7	23/53	6	2, 1-32 (4, 1-32)	1.45	3/53	$\hat{K}_1 = 0.3$ Strongly aggregated	All stages present.
<i>Littorina sitkana</i>	G	0.58	49/53	5.5	8, 1-214 (10, 1-214)	3.94	15/53	$\hat{K}_1 = 0.4$ Aggregated	Present year round.
<i>Collisella digitalis</i>	G	1	3/53	5.5	1	0.06	0/53	Random	Present year round.
<i>Littorina aleutica</i>	G	0.54	37/54	4	4, 1-129 (8, 1-129)	2.91	12/53		Present year round.
Small Species Whose Abundances Were Estimated from 50-mm-Diameter Subsamples of Quadrats									
<i>Cingula martyni</i>	G	0.57	7/11	3.8	234, 2-3810 (14, 2-3810)	3.27	1/11	$\hat{K}_1 = 0.3$ Strongly aggregated	All benthic stages present.
<i>Paranais littoralis</i>	O	1	2/11	3.5	190, 127-254 (190, 127-254)	0.91	0/11	$\hat{K}_1 = 0.2$ Strongly aggregated	Adults present.
<i>Calliopiella</i> (?) sp.	Ga	0.8	4/11	3.4	85, 24-345 (89, 51-345)	2.91	1/11	$\hat{K}_1 = 0.2$ Strongly aggregated	Adults and young present.
<i>Mysella aleutica</i>	B	1	1/11	3	127	0.27	0/11	$\hat{K}_1 = 0.1$ Strongly aggregated	Adults present.
<i>Cirratulus</i> Type II	Pc	1	0/11	3	64	0.36	0/11	$\hat{K}_1 = 0.1$ Strongly aggregated	

*Format modified after Table 2 of Fager and McGowan (1963).

†B, Bivalvia; G, Gastropoda; Ga, Gammaridea; O, Oligochaeta; Pc, Polychaeta.

‡Proportion of quadrats containing the species that was in this community corrected for differences in sample size between communities.

§Proportion of quadrats from this community that contained the species.

¶Average of ranks of fidelity and constancy for each species.

**Median and range of numbers of individuals per 0.25 m² in all quadrats in which the species was found and (in parentheses) these same statistics for quadrats from this community in which the species was found.

††Ranks for each species were averaged over 53 (large species) and 11 (small species) quadrats. The average ranks of the most abundant large and small species in the *Halosaccion*–*Fucus* quadrats were 6.02 and 8.91, respectively (1, least abundant).

‡‡Proportion of quadrats from this community in which the species was among those making up 50% of the individuals. Summation in each quadrat began with the most abundant species.

§§ $\hat{K}_1$, the first approximation of the exponent K of the negative binomial distribution. Overdispersion increases as K goes to 0. Dispersion was judged random if the quotient of the sample variance divided by the sample mean was not significantly different from one; the relation $\chi^2 = ns^2/\bar{x}$ was used for tests of significance.

benches. Sea stacks and vertical rock cliffs represent a smaller area of the intertidal region and were not sampled quantitatively. Therefore my sampling may have underestimated the species abundance, but this is unlikely. *Balanus glandula* is rare on the cobble and boulder beaches, which extend shore-

ward of and above the benches. Even when nearly optimal conditions for *B. glandula* are sought out on the island, such as on vertical surfaces in exposed localities, a distinct barnacle zone is rarely found, and even then individuals are scattered and do not form dense sheets as elsewhere in the

eastern North Pacific. There seems little doubt that lower *B. glandula* abundances are a real phenomenon at Amchitka.

Why are *B. glandula* abundances low at Amchitka? One might expect that, since the Aleutians are near the northern limit of *B. glandula*, populations at Amchitka may frequently suffer winter kill or poor reproductive success in spring owing to low temperatures. However, if we compare the long-term data on water temperature in the vicinity of Amchitka (inset, Fig. 3) with that for Kodiak Island, Alaska (Nybakken, 1969, Fig. 5), where *B. glandula* maintains populations, we see that the minimum water temperature recorded in the vicinity of Amchitka is higher than the mean water temperature in the coldest month of the year at Woman's Bay, Kodiak Island. Similarly, comparing air temperatures between the two islands, we find that the average monthly temperatures recorded at the Kodiak Naval Station in winter and early spring from 1942 through 1956 are about the same (29 to 36°F) (Rieger and Wunderlich, 1960) as those recorded at Amchitka from 1943 through 1948 (31 to 36°F) (Armstrong, 1971; Chap. 4, this volume), but the record lows at Kodiak (-5° to 10°F) are much lower than those at Amchitka (4° to 20°F). Further, large populations of *B. glandula* are present on islands to the east and west of Amchitka (Adak and Shemya). The apparent tolerance of *B. glandula* to a wide range of environmental conditions indicates that it is unlikely that such factors as low salinities or low oxygen content in the water are limiting *Balanus* populations at Amchitka.

Balanus cariosus populations are also in low abundance at Amchitka; so competitive exclusion of *B. glandula* by *B. cariosus* is ruled out. The results of previous studies of the effect of other species on *B. glandula* populations (Connell, 1970; Dayton, 1971) suggest that predation by *Thais lima* and/or disturbance by limpets of the genus *Collisella* and perhaps other herbivorous gastropods may be limiting *B. glandula* populations at Amchitka. Palmisano (1975) has found that 93.6% (N = 106) of the diet of *T. lima* on Amchitka consists of *Littorina* spp.; only 2.8% consists of barnacles (*B. glandula* and *B. cariosus*). I have made very few feeding observations of *T. lima* (N = 7), but on only one occasion did I see *Thais* feeding on a barnacle (a young *B. cariosus*). *Thais* may maintain its population size by preying on littorines and switch to barnacles when *B. glandula* recruitment makes it energetically worthwhile for *Thais* to do so. The threshold of barnacle density, above which the time required for *Thais* to search for its prey is significantly reduced and it becomes

energetically feasible for *Thais* to begin preying on *B. glandula*, may not be very high since barnacles are probably easier to capture and handle than littorines.

Dayton (1971) concludes from his studies that limpet disturbance alone cannot completely limit barnacle populations but does reduce barnacle recruitment. In the presence of both limpets and *Thais*, recruitment and survival of *B. glandula* are virtually nil. At Amchitka two species of limpets, *Collisella digitalis* and *C. strigatella*, show high fidelity for the *Halosaccion-Fucus* community. *Collisella digitalis* was rare in the *Halosaccion-Fucus* community because it was near its lower limit of vertical distribution. *Collisella strigatella* occurred somewhat more frequently in the *Halosaccion-Fucus* community ($c = 19/53$) than in the *Alaria-Hedophyllum* community ($c = 11/44$), but it was relatively uncommon in both communities. A third species, *C. pelta*, also occurred in the *Halosaccion-Fucus* community, but it was more common and more abundant in the *Alaria-Hedophyllum* community. Dayton's exclusion experiments included the above three species as well as a fourth, *Notoacmea scutum*. At Amchitka *N. scutum* rarely occurred in the *Halosaccion-Fucus* community. Densities for these four species at Amchitka are, for the most part, much lower than those recorded by Dayton. Nevertheless, *C. digitalis*, *C. strigatella*, and *C. pelta* may play an important role in limiting barnacle recruitment at Amchitka.

Sublittoral Invertebrates

A variety of semiquantitative sampling methods were used to collect sublittoral invertebrates and to assess their populations. These methods have included 215 shrimp trap sets, 37 crab trap sets, 26 minnow trap sets, and 11 amphipod trap sets. In addition, I made a limited number of direct observations (23 scuba dives) of sublittoral invertebrate communities to a depth of 34 m (112 ft). Sampling of communities below 34 m (112 ft) to a depth of 183 m (600 ft) was accomplished by dredging with rock and pipe dredges (10 hauls). Sublittoral and neritic invertebrates were also collected incidentally during sampling for fish with midwater and otter trawls, bottom gill nets, trammel nets, and long lines by Fisheries Research Institute biologists. Bottom longlines were particularly effective in capturing *Ptilosarcus* sp. Planktonic organisms were collected with a plankton pump. The appendix lists those sublittoral and neritic invertebrates which have been identified.

Sampling of sublittoral invertebrates with traps was patchy. Traps were set in the depth range 1 to

61 m (3 to 200 ft) and almost exclusively in Constantine Harbor on the Bering Sea side of the island and in Makarius Bay on the Pacific Ocean side; most were set in Constantine Harbor. The traps were both species and size selective, presumably selecting species the foraging behavior of which includes scavenging and which are in the size range that can enter yet be retained by the traps. The species that was most numerous and most frequent in and on the shrimp and crab traps was *Strongylocentrotus polyacanthus*. Other species frequently collected included *Fusitriton oregonensis*, *Leptasterias* spp., and *Buccinum* spp.

Traps set near the middle of Constantine Harbor on a sandy substrate (Fig. 4) consistently caught *Chionoecetes bairdi*. A total of 78 crabs ranging in carapace width from 24 to 77 mm were recorded from this area. The size of these crabs indicated that they were young; nevertheless, 20% of the females were gravid. The presence of adults in Constantine Harbor is not precluded by these trap data, but the largest of these crabs was well below the size selectivity of the traps. Relatively shallow bays, such as Constantine Harbor, may therefore be important in the early life history of this species.

Direct observations of sublittoral communities were made at various localities, mostly along the coast of the southeastern third of the island. Most observations were made in rocky inshore habitat dominated by four species of *Laminaria*, *Alaria fistulosa*, *Agarum cribrosum*, or *Thalassiophyllum clathrus*. Beneath this algal canopy the encrusting coralline algae (*Clathromorphum* spp.) usually covered the bedrock (Lebednik and Palmisano, Chap. 17, this volume).

The most common conspicuous benthic invertebrate encountered in the sublittoral communities was the small (up to 31 mm) *Strongylocentrotus polyacanthus*, which can reach densities of over 160 individuals per 0.25 m² (Barr, 1971). Other species that were found to be locally abundant in cracks between *Clathromorphum* plants were the brittle star *Ophiopholis aculeata* and the echiurid *Bonelliopsis alaskana*.

Where topographic relief was great, as at the edge of the intertidal benches, especially where massive blocks had been loosened and removed from the intertidal platform by waves, species richness appeared to be greatest, particularly on vertical surfaces. Here much of the rock surface was encrusted with sponges and tunicates. The stalked tunicate *Styela clavata* and various species of Actiniaria, including *Metridium* sp., were often numerous. Common motile species included *Margarites* sp., *Diadora* sp., dorid nudibranchs,

Musculus vernicosus, *Henricia* sp., and *Pteraster* sp. Occasionally the small crabs *Cancer oregonensis* and *Dermaturus mandtii* could be seen in pits and crevices in the rock surface. At the base of these blocks, shell and rock rubble usually accumulated, among which the tubes of *Chaetopterus variopedatus* could be seen.

All the dredge hauls were made on the Bering Sea side of the island. Of these, one-half were made in the outer sublittoral zone on the insular shelf and one-half were made in the upper bathyal zone. The appendix lists those species from the dredge hauls which have been identified along with the depths at which these species were caught.

Zoogeography

The Aleutian Island archipelago falls within the Aleutian province, a marine biogeographic subdivision of the Pacific boreal region. The Aleutian province extends from Dixon Entrance off British Columbia to Nunivak Island at about 60°N latitude (Briggs, 1974), but its western limit has never been precisely established. It has long been recognized that the Kamchatka current determines this limit (e.g., Ekman, 1953), but how far to the east does the influence of this current extend? As we shall see, the relatively high arctic boreal and low North American contributions to the fauna of the Commander Islands (Table 5) would indicate that these islands probably fall in the Asiatic High-Boreal province (Tzvetkova, 1975) and that the western limit of the Aleutian province falls somewhere to the east of them.

Zoogeographical Affinities

The following seven zoogeographical elements are present in the Amchitka invertebrate fauna: (1) "Widely distributed" species, including those invertebrates whose distributions extend into the tropics and southern hemisphere as well as those which are cosmopolitan or bipolar; (2) the "arctic-boreal" element, including circumpolar forms; (3) the "amphiboreal" element, including those species present in the boreal fauna of the Atlantic and Pacific Oceans but whose ranges do not extend into the arctic; (4) "North Pacific" species whose ranges extend to both Asiatic and North American shores; (5) "Asiatic" and (6) "North American" species whose ranges extend only to shores of the western and eastern Pacific, respectively; and, finally (7) the "endemic" element consisting of those species restricted to the Aleutian (and Commander) Islands. This definition of "endemic" refers to a much more limited geographic area than previously considered (O'Clair and Chew, 1972),

Table 5.—Number and Percent of Species of Intertidal and Shallow Sublittoral* Invertebrates of Three Major Taxonomic Groups at Amchitka Island and Two Groups in the Commander Islands Distributed According to Their Zoogeographical Affinities

	Zoogeographical elements†														Total
	Endemic		North American		Asiatic		North Pacific		Arctic—Boreal		Amphiboreal		Widely distributed		
	S‡	%	S‡	%	S‡	%	S‡	%	S‡	%	S‡	%	S‡	%	
	S‡	%	S‡	%	S‡	%	S‡	%	S‡	%	S‡	%	S‡	%	
Amchitka Island															
Polychaeta	1	5.9	4	23.5	2	11.8	2	11.8	3	17.6	0	0	5	29.4	17
Mollusca	3	7.5	10	25.0	5	12.5	15	37.5	6	15.0	0	0	1	2.5	40
Crustacea	1	3.3	10	33.3	6	20.0	12	40.0	0	0	1	3.3	0	0	30
Commander Islands															
Polychaeta§	4	14.8	2	7.4	2	7.4	1	3.7	10	37.0	1	3.7	7	25.9	27
Mollusca¶	1	3.1	2	6.2	7	21.9	14	43.8	8	25.0	0	0	0	0	32

*Restricted to species that are not found below a depth of 60 m.

†See text for geographical areas included in zoogeographical elements.

‡S, number of species.

§ Compiled from Annenkova (1934), who examined material from Bering Island only.

¶ Compiled from Dall (1884), Barabash-Nikiforov (1947), Skarlato (1960), and Golikov and Kussakin (1962).

reducing the endemic element considerably. For the purposes of discussion of the relative contributions of major faunal source areas to Amchitka, the present definition is preferable because it restricts "endemic" to "insular" only.

Table 5 shows the zoogeographical affinities of three major taxonomic groups of Amchitkan invertebrates. These three taxa were selected for illustration because they were the most abundantly represented macrofauna. The distributions of all the identified intertidal and shallow subtidal (to a depth of 60 m) species of these three groups were used to construct Table 5. Only intertidal and shallow subtidal species are considered here for the purposes of the discussion of the relative contributions of Asia and North America to the fauna of Amchitka. Species that do not "view" the Aleutian Islands as islands, i.e., those with very broad depth distributions, are excluded from the discussion. The depth limit was arbitrarily set at 60 m because this depth is shallower than all the passes separating major island groups in the Aleutians as well as many of the passes separating islands within these groups. The distributions of species included in Table 5 are noted following the species name in the appendix. The following sources were used to compile lists of species from the Commander Islands to obtain the percentages used in Table 5: Annenkova (1934) (polychaetes) and Dall (1884), Barabash-Nikiforov (1947), Skarlato (1960), and Golikov and Kussakin (1962) (mollusks).

Except in the Polychaeta (Table 5), widely distributed species do not represent a large component of the invertebrate fauna of Amchitka or of Bering Island. This holds true among the species

that have been identified whether or not species with broad depth distributions are included.

The amphiboreal element of the invertebrate fauna of Amchitka is either very small or nonexistent, depending on the taxonomic group (Table 5). Except for one crustacean, all species found on North Atlantic and North Pacific shores also range into the Arctic. These arctic-boreal species constitute from 0 (crustaceans) to 18% (polychaetes) of the shallow-water fauna of Amchitka. It is noteworthy that, for those groups for which we have comparable species lists from the Commander Islands, the arctic-boreal element on the Commander Islands is consistently greater (37% for polychaetes and 25% for mollusks) than that on Amchitka.

For the three taxonomic groups included in this discussion, between 12 and 40% (depending on the group) of the species restricted to the North Pacific are found on both Asiatic and North American shores. Of greater interest are the remaining North Pacific species, whose ranges extend either to Asiatic or North American shores but not to both.

Asian vs. North American Faunal Contributions

Amchitka lies midway between the tip of the Alaskan peninsula and the easternmost point on Kamchatka, yet, in all the major invertebrate groups considered here, the number of Asiatic species on the island is fewer than the number of North American species (Table 5). This trend of dominance of North American over Asian contributions is also found in marine fish on Amchitka

(Simenstad et al., Chap. 19, this volume; Wilimovsky, 1964), in terrestrial arthropods in the western Aleutians (Lindroth, 1963), and in the terrestrial flora of the islands in the vicinity of Amchitka: of the 33 species of vascular plants occurring in the Rat Island group (of which Amchitka is a member) whose ranges extend to continental Alaska or Kamchatka but not to both, 27 are found in Alaska but only 6 in Kamchatka (compiled from Hultén, 1960). (However, Hultén concluded that the flora of the Aleutians as a whole shows a closer affinity for Asia than for North America.) On the other hand, the Asiatic and North American contributions to the biota of Amchitka are about equal for marine algae (Lebednik and Palmisano, Chap. 17, this volume) and for birds (Emison, Williamson, and White, 1971; White, Williamson, and Emison, Chap. 11, this volume).

Why should an island equidistant between two major source areas have such a large representation of marine invertebrates from one source (North America) as compared with the other (Asia)? I have no information on extinction rates of marine invertebrates at Amchitka (although it seems a priori likely that, if a propagule lands on the island, the probability of it becoming extinct is independent of whether it is from Asia or North America). Further, I do not know whether Amchitka is at equilibrium with respect to its benthic marine invertebrates. Therefore I consider the question of disproportionate Asiatic and North American representation from the standpoint of differential rates of immigration alone.

Two important oceanographic features and one geologic feature affect the relative immigration rates of Asiatic and North American species: (1) the Alaskan Stream, (2) the Kamchatka Current, and (3) the Aleutian "stepping-stone" islands between Amchitka Island and the two continents. The Alaskan Stream is a westward-flowing current originating in the Gulf of Alaska (Fig. 1). It can affect the colonization of the Aleutians by providing directed dispersal westward along the Aleutian Chain for those species on the Alaskan Peninsula and in southeastern Alaska which are dispersed passively with surface-water currents. Included in this group of species are all those littoral and shallow sublittoral benthic invertebrates with benthic life stages dispersed by rafting as well as those with pelagic larvae. The Alaskan Stream extends as far west as longitude 170°E (Favorite, 1967; McAlister and Favorite, Chap. 16, this volume) and therefore probably exerts a negative effect on immigrants to Amchitka from Asia.

The Kamchatka Current is a southward-flowing stream of arctic water which passes be-

tween the coast of Kamchatka and the western Aleutian Islands (Fig. 1). As Dall (1884) and Ekman (1953, p. 156) have suggested, this current probably acts as a barrier to faunal exchange between northwestern America and northern Asia. [Briggs (1974) surmises that the "deep" between Kamchatka and the Aleutians is a barrier, but it is probably insignificant for most invertebrates, especially those with pelagic larvae.] I can envision two ways by which this current of arctic water reduces the colonization of the Aleutian Islands by Asiatic benthic invertebrates. First, the northern extent of the populations of some potential Asiatic emigrants would be forced southward, thereby increasing the distance over which propagules would have to disperse. If, for example, the northern limit of many potential Aleutian immigrants was forced southward from Kamchatka to the Kuril Islands, then Aleutian colonization from Asia would be reduced not only through an increase in the distance required for dispersal but also through a drastic reduction in the species pool because of the reduction in size of the nearest source area.

The second way by which the Kamchatka Current might reduce Aleutian colonization would be to sweep propagules emigrating from populations on Kamchatka and even on the Kuril Islands southward, which is normal to the direction that would facilitate immigration to the Aleutian Islands. We might expect this current to be particularly effective in reducing the Aleutian immigration of species that rely on pelagic larvae for dispersal. Many of these species spawn in the spring; Reid (1973) has reported extremely high rates of geostrophic transport of the Kamchatka Current in late winter and early spring.

The third important feature is the chain of Aleutian Islands which act as stepping stones between Amchitka and its two major faunal source areas, Asia and North America, and which increase the rate of immigration to Amchitka. Although these stepping stones occur both east and west of Amchitka, we would expect that the North American faunal source area would be favored over the Asiatic one because not only are there more major stepping stones to the east (13) than to the west (6) but also the total periphery of the islands between Amchitka and the Alaskan peninsula is roughly four times that of the islands between Amchitka and Kamchatka. Insular periphery has been used here instead of insular area because littoral and shallow sublittoral invertebrates are distributed around the periphery of the islands. Finally, the mean distance between major groups of islands lying east of Amchitka is approximately 50 miles (80 km), whereas it is 130 miles (210 km) between those to the west.

The net effect of these three features (the Alaskan Stream, the Kamchatka Current, and the other islands of the Aleutian Chain) is to reduce the immigration rate of colonizers to Amchitka from Asia to the extent that they are always outnumbered by North American species.

The endemic element is not represented by a large number of individuals in any of the three major taxonomic groups included in our discussion. Between one and four species, depending on the taxonomic group, are endemic to the Aleutian Islands.

A number of workers have noted a tendency toward a loss of dispersal power among endemic plants, insects, and birds on islands (for reviews, see MacArthur and Wilson, 1967; Carlquist, 1973). Although not yet well documented in marine invertebrates, we might expect this trend to hold for this group as well (Vermeij, 1972). Thus we might expect the endemic fauna of Amchitka to show a tendency toward direct larval development, a type that limits dispersal.

Throughout this discussion little has been said about the role of extinction in invertebrate colonization of Amchitka. In fact, we have little in the way of direct evidence relating to benthic invertebrate extinction on the island. But how do we account for the apparent failure of such species as *Pisaster ochraceus*, *Chthamalus dalli*, *Cancer magister*, *Telmessus cheiragonus*, *Cryptochiton stelleri*, *Thais lamellosa*, and *Mytilus californianus* (for other examples, see Palmisano and Estes, Chap. 22, this volume; Palmisano, 1975) to maintain populations on Amchitka when we consider the following? First, for marine benthic organisms oceanic islands like Amchitka can be thought of as mainland islands (MacArthur, 1972) in the sense that dispersal over water is much less hazardous for them than it is for such organisms as birds or insects. Second, all the species above have been recorded from mainland Alaska and on large islands near the Alaskan peninsula (Pilsbry, 1916; Oldroyd, 1924; 1927; Rathbun, 1930) and could presumably benefit from the Alaskan Stream and stepping-stone islands east of Amchitka to increase their immigration rates to Amchitka [*Cryptochiton stelleri*, *Chthamalus dalli*, and *Telmessus cheiragonus* have been reported from Kamchatka (Spassky, 1961)]. Finally, all the species above except *T. lamellosa* have planktotrophic larval development and consequently good dispersal power. These species would therefore be expected to have rather high Aleutian immigration rates. In fact, we have collected one individual each of *C. magister* and *M. californianus* on Amchitka, which indicates that immigration is occurring, but exten-

sive sampling has not turned up other representatives of these species. The remains of *T. cheiragonus* and *C. stelleri* in the form of an empty carapace and several shell plates, respectively, have been found on Amchitka, but I have no evidence of extant populations of these species there. I have nothing to indicate that *C. dalli* or *T. lamellosa* ever colonized the island. Accepting the premise that there has been ample time for these species to colonize Amchitka and that undetected populations do not exist on the island,* the alternative explanation for populations of these species being absent from Amchitka is that they have recently become extinct there.

I have so little information on the extinction of marine invertebrates in the Aleutians that I can only speculate about its causes on Amchitka. Competition may play a role in preventing *C. dalli*, *M. californianus*, and *T. lamellosa* from successfully colonizing Amchitka. The lower limit of distribution of *Chthamalus stellatus* on North Atlantic shores has been shown to be determined by competition for space with other barnacles of the genus *Balanus* rather than by predation (Connell, 1961a). Dayton (1971) reports that *C. dalli* suffers in competition with *B. glandula* and *B. cariosus*. Yet *B. glandula* is not common on Amchitka, and it seems unlikely that *Balanus* alone could exclude *C. dalli* from the island. Similarly, Harger (1972) argues convincingly that in California the two mussels *Mytilus edulis* and *M. californianus* compete for space, although *M. californianus* is never completely excluded except perhaps in very sheltered areas. Whether *M. californianus* at the edge of its geographic range could be excluded by *M. edulis* from an island that contains no habitats as exposed as those on the outer coasts of California is a matter only for speculation.

The low abundance of *Balanus cariosus* and *B. glandula* on Amchitka may support but one species of predatory snail. Why this snail should be *Thais lima* and not *T. lamellosa* may have to do with the former's adaptations. *Thais lima* is very similar morphologically to *T. emarginata*; in fact, Kincaid (1964) considered the two species to be

*This latter assumption is almost certainly true for the intertidal species *M. californianus*, *T. lamellosa*, and *C. dalli*. We cannot be completely certain that it holds for the sublittoral species *C. magister*, *T. cheiragonus*, and *C. stelleri* because our sublittoral sampling was not as extensive as our littoral work (see the appendix). If populations of these species do exist on Amchitka, their population levels are probably so low that they run a high risk of extinction from random population fluctuations.

synonymous. *Thais lima* and *T. emarginata* are small compared to other members of the genus, and both possess a comparatively thin shell, a large opening, and a short spire. Connell (1970) suggests that these adaptations allow *T. emarginata* to persist at upper shore levels provided that its main food supply, *B. glandula*, is very dependable. At low shore levels the thin shell of *T. emarginata* makes it vulnerable to predation by crabs that live there, whereas *T. lamellosa*, which has a thicker shell, avoids this predation (Connell, 1970). On Amchitka, crabs inhabiting the intertidal zone are *Dermaturus mandtii*, *Hapalogaster grebnitzkii*, *Pagurus hirsutiusculus*, *Cancer oregonensis*, and *Pugettia gracilis*. All these species are small and in low abundance* and it is unlikely that any of them prey on *Thais*. *Thais lima* may therefore be free of crab predation at low shore levels on Amchitka. If, in addition, *T. lima*, because of its smaller size and thinner shell, can subsist on a lower rate of intake of food than *T. lamellosa*, as Connell (1970) has suggested for *T. emarginata* vs. *T. lamellosa*, then *T. lima* may be able to exclude *T. lamellosa* from lower shore levels. (However, there is no documented evidence of competitive exclusion among thaisids.)

Another possible cause for extinction of marine invertebrates on Amchitka is predation, especially by sea otters (*Enhydra lutris*) (see Palmisano and Estes, Chap. 22, this volume). Size selective predation by otters on *M. californianus*, which grows larger and matures later than *M. edulis* (Harger, 1972), may contribute to the former species being excluded from Amchitka. However, *M. californianus* is also absent from Shemya Island where sea otter predation is negligible. Sea otter predation may also be responsible for the extinction or near extinction of *C. magister*, *T. cheiragonus*, and *C. stelleri* populations on Amchitka.

Effects of Cannikin

Immediate Effects. The underground nuclear test, Cannikin (Nov. 6, 1971), produced several effects traumatic to intertidal invertebrates. Immediate effects associated with the passage of the ground shock wave (Merritt, 1972) could have caused mortality in the following ways:

1. Some invertebrates dislodged or overturned by the shock wave would be unable to reattach (barnacles and ascidians) or right them-

selves (limpets) and would be subject to starvation, desiccation, and predation.

2. Animals were probably crushed by falling boulders and rubble overturned or propelled upward from the bench surface when the shock wave passed.

3. Immersed organisms were subjected to overpressures that may have been as high as 100 psi (Merritt, 1972) followed by underpressures and cavitation.

These immediate effects alone would not have had a profound influence on community structure.

A more important source of mortality to invertebrate populations on those parts of the intertidal benches near the bases of cliffs and sea stacks was burial by rockfalls and turf slides. Although the total volume of these falls and slides has been estimated by the U. S. Geological Survey to be 35,000 m³ (Kirkwood, 1974), most of this material was deposited on the beach shoreward of the intertidal benches and affected intertidal organisms only in localized areas (Lebednik and Palmisano, Chap. 17, this volume, and personal observations). At the edges of the benches, bench spall resulted in large chunks of rock and accompanying organisms plunging from the edge of the bench into the sea (however, some of this material probably washed onto the bench surface). The fate of animals not killed in these rockfalls is unknown. Most of the evidence accumulated so far indicates that intertidal animals are excluded from the sublittoral area by predators and competitors (Connell, 1972). Intertidal invertebrates that survived the plunge into the sublittoral area probably will not be able to maintain populations there.

Long-Term Effects. All the disturbances discussed above, although by no means inconsequential to intertidal invertebrate communities, are relatively transitory in ecological time; i.e., though mortality may be high as a result of these disturbances, recolonization is rapid compared with the generation time of most of the species involved unless the habitat is made unsuitable for recolonization. The most disruptive and lasting disturbance to intertidal communities resulting from Cannikin was the permanent uplifting of the Bering Sea coast near the site of Cannikin. Detectable uplift in the range of 3.4 cm (1.3 in.) to 1.1 m (3.6 ft) was recorded along at least 7.8 km (4.8 miles) of coastline (Kirkwood and Fuller, 1972, Table A-5). Lebednik and Palmisano (Chap. 17, this volume) have detected mortality in algal populations along at least 6 km (4 miles) of coast (Fig. 13). I consider below changes in invertebrate populations attributable to uplifting.

*In May 1968 numerous individuals of *D. mandtii* were seen in the *Laminaria* community at Makarius Bay (J. S. Isakson, personal communication), but subsequent attempts to find crabs there have proved fruitless.

Fig. 13—(a) Distribution and relative magnitude of algal die-off due to Cannikin along the section of coastline shown on the map in part (c). Detectable, from one to a few species showing die-off. Moderate, a few species showing extensive die-off (more than about one-third of the total population). Severe, all abundant species showing extensive to complete die-off. (Data from Lebednik and Palmisano, Chap. 17.)

(b) Vertical displacement at several locations along the same section of coastline as part (a). (Data from Kirkwood and Fuller, 1972, Table A-5.)

(c) Map of a section of Bering Sea coastline adjacent to Cannikin surface zero (SZ). Points along the shore that are depicted in parts (a) and (b) are directly above the appropriate locations on map.

The 25 plots initially established at IA-2 were uplifted from 75 cm to 1.1 m (3.6 ft), depending on the plot, as a result of Cannikin (Table 6). Sixteen were uplifted above extreme high water of spring tides for the Bering Sea coast of Amchitka (146 cm in 1969); four were lifted above mean high water. Five plots were buried by rockfalls.

Figures 14 and 15 show the changes in mean species counts with time following Cannikin for three intertidal communities at IA-2 and IA-3, respectively, compared with Makarius Bay (control). The plots in the *Halosaccion-Fucus* community at IA-2 were divided into two groups. The first group contains plots nearer the seaward edge of the bench (outer plots). The second group contains plots nearer the shoreward edge of the bench away from the area of frequent wetting by wave splash and salt spray when emersed (inner plots). IA-3 and Makarius Bay are relatively sheltered, and all plots at these sites were subject to the same degree of exposure; therefore outer and inner plots were not distinguished. All species on the plots that could be distinguished are included in Figs. 14 and 15. Species of Platyhelminthes, Nemertea, Oligochaeta, Nematoda, and Ectoprocta were not distinguished. Polychaetes, except *Nereis pelagica*, *Dexiospira semidentata*?, and *Dexiospira* sp., and gammarids, except *Parallorchestes ochotensis* and *Orchestia* sp., were lumped into Polychaeta and Gammaridea, respectively. Actiniaria were divided into species that were and that were not members of the Family Actiniidae.

Species counts at IA-2 began declining in all communities immediately after Cannikin (Fig. 14). From the beginning the greatest source of mortality of invertebrates not crushed or buried by rock and soil was prolonged emersion due to uplift, especially for the sessile species, such as sponges, sedentary polychaetes, bivalves, and ascidians. Some motile species at the seaward edges of the benches which were not thrown into the water with the passage of the shock wave may have migrated to lower levels soon after uplift. Predation by gulls and oyster catchers may also have been an important source of mortality in the first few days following uplift. During this period large flocks of gulls (*Larus glaucescens*) and oyster catchers (*Haematopus bachmani*) were seen at IA-2 (C. Simenstad, personal communication). Also, a large number of overturned and empty limpet shells (*Collisella* spp.) were observed on the bench. How much of the activities of these birds can be attributed to predation and how much to scavenging of dead and dying animals is not known.

The fifteen plots established at IA-3 were uplifted from 47 to 56 cm, depending on the plot (Table 6). Only one plot was uplifted above extreme high water of spring tides. However, probably because IA-3 is more sheltered than IA-2, mean species counts there declined similarly to but less drastically than at IA-2 (Fig. 15). The sole exception to this trend was plot 1.

Plot 1 (Table 7) was established in the *Laminaria* community pre-Cannikin. It had been up-

Table 6—Physical Survey Data for 0.25-m² Plots at IA-2 and IA-3 Before and After Cannikin*

Plot	Elevation, cm		Upward displacement, cm	Plot	Elevation, cm		Upward displacement, cm
	Before	After			Before	After	
IA-2				IA-2 (Continued)			
1	40.7	150.7	110.0	24	59.6	138.5	78.9
2	57.0	157.7	100.7	25	34.3	122.1	87.8
3	51.4	151.0	99.6	26	38.2†	133.1	94.9
4	41.8	139.6	97.8	27	58.3	153.2	94.9
5	139.1	234.0	94.9				
6	68.8	Buried					
7	15.4	Buried					
8	12.6	Buried					
9	47.7	145.6	97.9	1	16.3	70.5	54.2
10	131.9	229.5	97.6	2	20.4	72.8	52.4
11	80.5	177.7	97.2	3	36.9	89.4	52.5
12	6.2	99.1	92.9	4	28.6	80.8	52.2
13	45.2	138.5	93.3	5	67.8	124.3	56.5
14	53.7	146.5	92.8	6	40.6	88.4	47.8
15	81.2	171.8	90.6	7	20.4	67.9	47.5
16	69.0	Buried		8	43.0	90.6	47.6
17	33.4	117.5	84.1	9	53.3	100.5	47.2
18	66.6	153.5	86.9	10	44.8	92.2	47.4
19	99.8	189.5	89.7	11	59.1	Buried	
20	66.0	156.4	90.4	12	93.8	Buried	
21	20.0	Buried		13	43.2	92.3	49.1
22	47.5	122.2	74.7	14	32.6	82.7	50.1
23	47.5	125.6	78.1	15	32.7	83.5	50.8

*Compiled by P. A. Lebednik from Holmes and Narver and Fisheries Research Institute survey data.

†Preevent elevations of plots 26 and 27 were back-calculated assuming that each plot was uplifted equally with the nearest original IA-2 plot.

lifted 54 cm to an elevation of 70 cm. Species counts on this plot at first declined after Cannikin but increased again by 3 months post-Cannikin. Part of this increase was an artifact in that species, such as *Actiniaria* spp., *Dexiospira* sp., *Phascolosoma agassizii*, and *Balcis randolphi* (Table 7), were probably present pre-Cannikin but were missed in the dense *Laminaria* holdfast cover. Also contributing to the increased species count on plot 1 at 3 months was the addition, to the remnant populations of species of the *Laminaria* community, of species common to higher levels in the intertidal area, such as *Littorina* spp., which had migrated into the plot when their former habitat was uplifted above the intertidal area (Table 7). By 7 months postevent, the character of the fauna on plot 1 had changed from *Laminaria* community to a fauna containing species with broader vertical ranges and species of higher intertidal levels. As we will see later, IA-3 plot 1 is the only plot at either IA-2 or IA-3 to show signs of recolonization by intertidal organisms after 33 months postevent.

The total number of species seen preevent in each community decreased steadily after Cannikin to relatively stable levels within 1 year (Fig. 16). Conversely, the total number of new species not previously recorded on plots in each of the three communities increased. The new species consisted chiefly of species from upper intertidal levels, especially the supralittoral fringe, and included Collembola, Diptera (*Saundersia marinus* and *Paraclytus alaskensis*), Acarina (*Neomolgus littoralis*, *Parasitus* sp., etc.), *Ligia pallasii*, and the gammarid *Orchestia* sp. The only intertidal species that persisted throughout the year on the uplifted plots were the gastropods *Littorina* spp.

The control at Makarius Bay showed a slight decrease in mean species count per plot in February 1972 (3 months postevent) and then a return nearly to October 1971 levels by August 1972 (9 months postevent) (Figs. 14 and 15). However, the decline was only 23 to 24% of the October 1971 levels, depending on the community. The decrease by February 1972 at IA-2 varied from 3

Fig. 14—Mean species counts for each algal zone before and after Cannikin at IA-2 and Makarius Bay (control). Asterisk indicates a sample size of 1. All macroscopic species at IA-2 with distinguishable individuals are included. Anemones, polychaetes, and gammarids, which could not be distinguished to species in the field, were lumped into their respective taxonomic groups. At Makarius Bay all identifiable species with distinguishable individuals retained by a 1-mm sieve are included.

to 100% of the September 1971 levels, depending on the community. The decrease at IA-3 was 53% and 58% in the *Halosaccion-Fucus* and *Alaria-Hedophyllum* communities, respectively. The only *Laminaria* community plot (IA-3 plot J) showed an increased species count of 36%. I attribute the decrease in mean species count in February 1972 at Makarius Bay to seasonal changes in species composition. The Makarius Bay grid was not sampled at 17 and 30 and 33 months postevent because of inadequate field time and poor tides, respectively. The grid was sampled at 22 months, but the data are not included here. General observation of the grid at these sampling times did not reveal obvious departures from the normal pattern of seasonal change in the intertidal communities at Makarius Bay.

The mean number of individuals per plot in all communities at IA-2 and IA-3 generally decreased throughout the year following Cannikin (Figs. 17 and 18, respectively). However, the decline was erratic in some communities. At IA-2 the outer

Halosaccion-Fucus and the *Alaria-Hedophyllum* communities showed increases in the mean number of individuals per plot, especially in April and June 1972. At IA-3 the *Laminaria* and *Alaria-Hedophyllum* plots showed increases in the mean number of individuals of comparable magnitude in August 1972. Both of these increases are accounted for by increases in the abundances of *Littorina* spp., especially *L. atkana*. Further, littorines too small to be assigned to species in the field also showed increases in April, June, and August 1972 (Figs. 19 and 20).

The drop in the mean number of individuals per plot in the *Halosaccion-Fucus* community at Makarius Bay is probably seasonal (Figs. 17 and 18). *Halosaccion glandiforme* dominates this community at Makarius Bay and shows seasonal die-off in late fall and winter which extends to late spring (Lebednik and Palmisano, Chap. 17, this volume, and personal observations). The drop in the number of individuals may be due to the loss of the moderating effect of the algae on the microclimate

Fig. 15—Mean species counts for each algal zone before and after Cannikin at IA-3 and Makarius Bay (control). Asterisk indicates a sample size of 1. All macroscopic species at IA-3 with distinguishable individuals are included. Anemones, polychaetes, and gammarids, which could not be distinguished to species in the field, were lumped into their respective taxonomic groups. At Makarius Bay all identifiable species with distinguishable individuals retained by a 1-mm sieve are included.

of the invertebrates and perhaps to a reduction in the spatial heterogeneity in this community in winter.

After 1 year post-Cannikin, mean species counts per plot at IA-2 and IA-3 remained in the range 0 to 4 (Figs. 14 and 15, respectively). The total number of species formerly present in each community before Cannikin at both IA-2 and IA-3 never exceeded seven in those communities during the period of 12 to 33 months postevent (Fig. 16). Counts of individuals also remained low during this period, seldom exceeding a mean of 10 individuals per plot at IA-2 (Fig. 17). In May 1974 (30 months postevent), former *Halosaccion-Fucus* community plots at the seaward edges of the benches at IA-2 showed large numbers of tiny pink mites (*Acarina* sp.), but these mites were present in large numbers on only one plot (formerly in the *Alaria-Hedophyllum* community) in August 1974. These tiny abundant mites also accounted for most of the increase in the mean number of individuals in plots in the *Alaria-Hedophyllum* and *Halosaccion-*

Fucus communities at IA-3 in May 1974. Large numbers of littorines, especially *L. atkana* (Fig. 20), on some plots kept the mean number of individuals relatively high in the former *Alaria-Hedophyllum* community at IA-3 in August 1974. Most of the invertebrates observed on the IA-2 and IA-3 plots after 1 year postevent were in moist depressions and crevices or beneath pieces of dead kelp which were tossed up on the benches during storms and which had become hung up on the nails marking the plots. Other species, such as the flies *Saundersia marinus* and mites *Neomolgus littoralis*, moved through the plots very rapidly.

IA-3 plot 1 was the only plot at either IA-2 or IA-3 that showed some signs of recovery by the end of the study. Species counts there reached a minimum sometime between 12 and 22 months postevent but then began showing some signs of recovery. By 17 months postevent a few young *Fucus distichus* plants were seen on the plot (Lebednik and Palmisano, Chap. 17, this volume), and by 33 months the percent cover of *F. distichus*

Table 7—Species Abundances per 0.25 m² on IA-3 Plot 1 Before and After Cannikin

Species	Taxon*	Months before Cannikin†	Months after Cannikin										
		2	1	3	5	7	9	11	17	22	30	33	
<i>Scypha compressa</i> †	P	+‡	1										
<i>Halichondria panicea</i> †	P	25	12	25									
Actiniidae spp.	C	+	1	2									
<i>Dexiospira semidentata</i>	Pc			2(32)§									
<i>Lepidochitona aleuticus</i>	Am	49	1	8	2(5)	1							
<i>Haloconcha minor</i>	G	4	1	1									
<i>Cingula</i> spp.¶	G	+	2	22	16	15	142	22				7	
<i>Mitrella amiantis</i>	G	16		1				1					
<i>Buccinum baeri morchianum</i>	G	3											
<i>Margarites beringensis</i>	G	18	8	3									
<i>Idotea wosnessenskii</i>	I	15	8				26				1	27	
<i>Parallorchestes ochotensis</i>	Ga	43	3										
<i>Leptasterias aleutica</i>	A	2											
<i>Cucumaria vegae</i>	H	5		2	(1)								
? <i>Styela coriacea</i>	As	8	20	38									
Actiniaria sp.	C			6			3	2					
Nemertea spp.											1		
Oligochaeta sp.							3			3			
<i>Phascolosoma agassizii</i>	S			1	1		1						
<i>Schizoplax brandtii</i>	Am						1						
<i>Collisella pelta</i>	G			(2)									
<i>Notoacmea scutum</i>	G			(1)									
<i>Balcis randolphi</i>	G			1									
<i>Littorina aleutica</i>	G				3	2	3		1	1		2	
<i>Littorina atkana</i>	G			1	5	10	80	3	1	10	262	535	
<i>Littorina sitkana</i>	G			2		13	103		3		17	50	
<i>Alvinia aurivillii</i>	G			2	5	2	1						
<i>Musculus vernicosus</i>	B				1	1							
<i>Mytilus edulis</i>	B								1				
<i>Turtonia minuta</i>	B			5	7(+)	2	31	11	3	8	57	33	
<i>Macoma</i> sp.	B					1							
<i>Exosphaeroma amplicauda</i>	I		1									4	
<i>Pontogeneia makarovi</i>	Ga							2				17	
<i>Anisogammarus conferviculus</i>	Ga											3	
Gammaridea spp.				1							1		
<i>Liparocephalus brevipennis</i>	In										2		
<i>Saundersia marinus</i>	In										11A**		
<i>Paraclunio alaskensis</i>	In					1A				2A			
Diptera sp.	In									2A			
Insecta spp.										1L	6L		
<i>Neomolgus littoralis</i>	Ac					1							
Acarina spp.							2				62		

*A, asteroidea; Ac, acarina; Am, amphineura; As, ascidiacea; B, bivalvia; C, cnidaria; G, gastropoda; Ga, gammaridea; H, holothuroidea; I, isopoda; In, insecta; P, porifera; Pc, polychaeta; S, sipuncula.

†Abundance is percent cover.

‡Plus signs indicate relative abundance: +, present.

§Numbers in parentheses indicate number of dead individuals.

¶*Cingula aleutica* and *C. martyni* not distinguished.

**Letters accompanying abundances refer to life stages: L, larva; A, adult.

Fig. 16—Replacement following Cannikin of original species by species not previously recorded on plots in three communities at IA-2 and IA-3 combined. The numbers directly above the vertical bars indicate the number of plots sampled.

had increased to 40% (C. Simenstad, personal communication). Invertebrate populations increased in size with the increase in *Fucus* cover (Fig. 18 and Table 7), but the species count was well below the mean species count recorded for undisturbed *Halosaccion-Fucus* plots by 33 months postevent. Apparently plot 1 at 33 months postevent was near the upper limit of the *Halosaccion-Fucus* community (the highest intertidal community) for the degree of exposure at IA-3.

How much of the pre-Cannikin intertidal zone was uplifted into the supralittoral fringe? Thirty-three months after Cannikin was detonated, I made an estimate of this area in the field by superimposing plane geometric figures on the bench surface. The areas included within the figures were essentially bare rock containing scattered supralittoral invertebrates and no macrophytes. The estimate arrived at was 5.8 ha (14.3 acres). This estimate is conservative because:

1. The method treats the bench as a plane surface and ignores irregularities.

2. The estimate excludes areas of offshore islets that could not be reached.

3. The estimate does not include uplifted bench area east of Banjo Point or west of Sand Beach Cove. Although the length of coastline included in this estimate is only half that wherein algal damage was detectable (Lebednik and Palmisano, Chap. 17, this volume), the area of bench outside this length of coastline that was uplifted out of the intertidal zone is probably small by comparison.

Before Cannikin the intertidal zone was a nearly horizontal plane between Banjo Point and Sand Beach Cove. In this stretch of coastline, the new intertidal area is a steep slope at the outer edge of the uplifted bench and occupies a much smaller area than before. Finally, intertidal recolonization of the former bench surface may not be complete; there is some evidence that the uplifted bench is being eroded. By spring 1974 mechanical and chemical weathering appeared to have reduced the level of the uplifted bench by 1 to 2.5 cm,

Fig. 17—Mean number of individuals in plots for each algal zone before and after Cannikin at IA-2 and for the control, Makarius Bay (circled symbols). Asterisk indicates a sample size of 1. Species not retained by a 2-mm sieve, such as oligochaetes, *Turtonia minuta*, and *Cingula* spp., gammarids, except *Parallorchestes ochotensis* and *Orchestia* spp., polychaetes, except *Nereis pelagica*, and the holothurian *Cucumaria vegae* are excluded. All gammarids and polychaetes at Makarius Bay are excluded.

depending on bedrock lithology (Kirkwood, 1974). However, the rate seems to be decreasing, and it is uncertain when this erosion will bring these uplifted areas back down to sea level. The fate of the upper surface of the rock bench lifted above the intertidal area is still in doubt.

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Fig. 18.—Mean number of individuals in plots for each algal zone before and after Cannikin at IA-3 and for the control, Makarius Bay (circled symbols). Asterisk indicates a sample size of 1. Species not retained by a 2-mm sieve, such as oligochaetes, *Turtonia minuta*, and *Cingula* spp., gammarids, except *Parallorchestes ochotensis* and *Orchestia* spp., polychaetes, except *Nereis pelagica*, and the holothurian *Cucumaria vegae* are excluded. All gammarids and polychaetes at Makarius Bay are excluded.

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Fig. 19—Mean abundances of littorines on 0.25-m² plots in three communities before and after Cannikin at IA-2. H-F_i, *Halosaccion-Fucus* community inner plots; H-F_o, *Halosaccion-Fucus* community outer plots; A-H, *Alaria-Hedophyllum* community; L, *Laminaria* community.

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Fig. 20—Mean abundances of littorines on 0.25-m² plots in two communities [*Halosaccion-Fucus* (H-F) and *Alaria-Hedophyllum* (A-H)] and abundances on one plot in the *Laminaria* (L) community before and after Cannikin at IA-3. Data collected in the *Laminaria* community 15 months before Cannikin were lost at sea.

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APPENDIX: ANNOTATED SPECIES LIST OF THE INVERTEBRATES AT AMCHITKA ISLAND, ALASKA

The following species list is a partial list of the species of invertebrates collected by Fisheries Research Institute personnel in the vicinity of Amchitka Island, Alaska. A number of specialists have contributed their expertise to the preparation of this list. These specialists are listed below and are acknowledged preceding the taxonomic groups or species they identified.

- Dr. Donald P. Abbott, Hopkins Marine Station of Stanford University, Pacific Grove, Calif. *Styela clavata*.
- Ms. Suzanne Allyson, Research Branch, Biosystematics Research Institute, Agriculture Canada, Ottawa, Ontario, Canada. Lepidoptera.
- Dr. Gerald J. Bakus, University of Southern California, Los Angeles, Calif. *Halichondria panicea*.
- Dr. Karl Banse, Department of Oceanography, University of Washington, Seattle, Wash. *Syllis*.
- Mr. Louis Barr, National Marine Fisheries Service, Biological Laboratory, Auke Bay, Alaska. *Rhinolithodes wosnessenskii*.
- Dr. Edward C. Becker, Research Branch, Biosystematics Research Institute, Agriculture Canada, Ottawa, Ontario, Canada. Coleoptera.
- Dr. Edward L. Bousfield, National Museum of Natural Sciences, Ottawa, Ontario, Canada. Gammaridea.

- Dr. J. Milton Campbell, Research Branch, Biosystematics Research Institute, Agriculture Canada, Ottawa, Ontario, Canada. Coleoptera.
- Dr. David G. Cook, Department of the Environment, Fisheries and Marine Service, Ottawa, Ontario, Canada. Oligochaeta.
- Mr. Matthew Dick, 1902 Statc St., Alamosa, Colo. Bryozoa.
- Dr. Maurcen E. Downey, Department of Invertebrate Zoology, National Museum of Natural History, Washington, D. C. Asteroidea.
- Dr. Arthur R. Fontaine, Department of Biology, University of Victoria, Victoria, British Columbia, Canada. *Bonelliopsis*.
- Ms. Madeline Green, College of Fisheries, University of Washington, Seattle, Wash. *Japetella heathi*.
- Dr. Olga Hartman, deceased, formerly at the Allan Hancock Foundation, University of Southern California, Los Angeles, Calif. *Cirratulus*.
- Dr. Melville H. Hatch, Burke Memorial Museum, University of Washington, Seattle, Wash. *Liparocephalus*.
- Dr. Charlotte Holmquist, Sekt. Evertebratzool, Naturhistoriska Riksmuseet, Stockholm, Sweden. *Paracanthomysis kurilensis*.
- Dr. Paul L. Illg, Department of Zoology, University of Washington, Seattle, Wash. *Blakeanus*.
- Dr. Margit Jensen, Zoological Museum, University of Copenhagen, Copenhagen, Denmark. *Strongylocentrotus*.
- Dr. A. Myra Keen, Department of Geology, Stanford University, Stanford, Calif. Mollusca.
- Dr. Allan J. Kohn, Department of Zoology, University of Washington, Seattle, Wash. *Phascolosoma*.
- Dr. Eugene N. Kozloff, Department of Zoology, University of Washington, Seattle, Wash. *Tetrastemma*.
- Ms. Diana R. Laubitz, National Museum of Natural Sciences, Ottawa, Ontario, Canada. *Cercops*.
- Dr. Ulf Lie, Biological Station Espengrend, Blomsterdalen, Norway. Gammaridea.
- Dr. Evert E. Lindquist, Research Branch, Biosystematics Research Institute, Agriculture Canada, Ottawa, Ontario, Canada. Acarina.
- Dr. James H. McLean, Los Angeles County Museum of Natural History, Los Angeles, Calif. Mollusca.

- Dr. Carl F. Nyblade, Department of Zoology, University of Washington, Seattle, Wash. Paguridae.
- Dr. Rita M. O'Clair, Friday Harbor Laboratories, Friday Harbor, Washington. Polychaeta.
- Mr. Gordon W. O'Connell, Department of Biology, University of Victoria, Victoria, British Columbia, Canada. Pycnogonida.
- Dr. Donald R. Oliver, Research Branch, Biosystematics Research Institute, Agriculture Canada, Ottawa, Ontario, Canada. Diptera.
- Dr. Bruce Ott, Institute of Marine Sciences, McGill University, Montreal, Quebec, Canada. Porifera.
- Dr. David L. Pawson, Department of Invertebrate Zoology, National Museum of Natural History, Washington, D. C. Echinodermata.
- Dr. Stephen Prudhoe, Department of Zoology, British Museum (Natural History), London, England. Turbellaria.
- Ms. Famida Rafi, National Museum of Natural Sciences, Ottawa, Ontario, Canada. *Idotea*.
- Dr. Gordon A. Robilliard, Woodward-Envicon, Inc., San Diego, Calif. Nudibranchia.
- Dr. Mary E. Roussel, Research Branch, Biosystematics Research Institute, Agriculture Canada, Ottawa, Ontario, Canada. Diptera.
- Mr. Kenneth Sebens, Department of Zoology, University of Washington, Seattle, Wash. Actiniaria.
- Mr. Ronald Shimek, Department of Zoology, University of Washington, Seattle, Wash. *Suavodrilina*.
- Mr. Peter N. Slattery, Moss Landing Marine Laboratories, Moss Landing, Calif. Gammaridea.
- Dr. Herbert J. Teskey, Research Branch, Biosystematics Research Institute, Agriculture Canada, Ottawa, Ontario, Canada. Diptera.
- Mr. Gregory J. Tutmark, 2200 Northeast 75th Street, Seattle, Wash. Cephalopoda and Crustacea.
- Dr. Charles W. Thayer, Department of Geology, University of Pennsylvania, Philadelphia, Pa. Brachiopoda.

Unless otherwise noted, I identified the rest of the species included in the list from the literature, and references are included following the names, authors, and dates of these species. Additional annotations include the vertical distribution of the species in the vicinity of Amchitka, and, for those species covered in Table 5, the geographical distribution. (Species in those groups covered whose ranges extend to a depth greater than 60 m were not included in Table 5.) Information on intertidal

invertebrates occurring at the five main study sites includes the population statistics fidelity (*f.*), constancy (*c.*), and abundance (*a.*). Classification generally follows Barnes (1974). Specimens have been deposited in the invertebrate collections of the National Museum of Natural Sciences, Ottawa, and the College of Fisheries, University of Washington. Abbreviations used in this species list are listed below.

a (abundance), median and range of numbers of individuals per 0.25 m² in quadrats in which the species was found.

c (constancy), proportion of quadrats from the community to which the species was assigned that contained the species.

f (fidelity), proportion of all quadrats containing the species that was in the community to which the species was assigned. A species was assigned to that community where the value of *f.* was greatest.

NMNS, National Museum of Natural Sciences, Ottawa, Canada.

USNM, National Museum of Natural History, Washington, D. C.

Phylum Porifera (Unless otherwise noted, all Porifera identified by B. Ott and deposited in the NMNS.)

Class Calcarea

Scypha compactum (Lambe, 1894).
Sublittoral, 6 m.

Scypha compressa (Fabricius, 1780).
Compared with NMNS specimens of *Grantia monstrosa* (Breitfuss, 1898) [= *S. compressa* (see Burton, 1963)] from Bering Island. Verified by B. Ott. See Table 2 for population statistics.

Leucandra taylori Lambe, 1900.
Alaria-Hedophyllum community to 91 m.

Leuconia pyriformis (Lambe, 1894).
Alaria-Hedophyllum community to 6 m.

Leuconia heathi (Urban, 1905). *Laminaria* community to 183 m.

Leuconia sp. A. Sublittoral, 6 to 24 m.
Rhabdodermella nuttingi Urban, 1905.
Sublittoral, 91 m.

Class Hyalospongia

Rhabdocalyptus dawsoni (Lambe, 1893). Sublittoral, 183 m.

Hyalospongia sp. Sublittoral, 183 m.

Class Demospongiae

Haliclona permollis (Bowerbank, 1866). Sublittoral, 6 m.

Haliclona sp. Sublittoral, 91 m.

Gellius sp. Sublittoral, 183 m.

- Sigmatocia edaphus* de Laubenfels, 1930. Sublittoral, 55 m.
- Isodictya quatsinoensis* (Lambe, 1893). Sublittoral, 6 to 24 m.
- Mycale hispida* (Lambe, 1894). Sublittoral, 6 to 24 m.
- M. lingua* (Bowerbank, 1866). Sublittoral, 18 to 24 m.
- M. loveni* (Fristedt, 1887). Sublittoral, 91 m.
- M. helios* (Fristedt, 1887). Sublittoral, 91 m.
- Mycale* sp. Sublittoral, 91 m.
- Anthoarcuata graceae* Bakus, 1966. Sublittoral, 6 to 24 m.
- Microciona primitiva* Koltun, 1955. Sublittoral, 91 to 183 m.
- Iotrochota magna* Lambe, 1895. Specimens collected by R. Martin. Sublittoral, 15 to 23 m.
- Lissodendoryx amaknakensis* (Lambe, 1895). Sublittoral, 6 m.
- L. firma* (Lambe, 1895). *Laminaria* community to 91 m.
- Stelodoryx alaskensis* (Lambe, 1895). Sublittoral, 6 to 55 m.
- Wigginsia wigginsii* de Laubenfels, 1953. Sublittoral, 183 m.
- Myxilla lacunosa* Lambe, 1893. Sublittoral, 6 m.
- Halichondria panicea* (Pallas, 1766). Identification by G. J. Bakus of specimens collected by J. F. Palmisano. *Laminaria* community; f, 0.53; c, 0.66; a, 12.6%, 1 to 55%.
- H. lambei* Brønsted, 1933. Sublittoral, 6 to 183 m.
- Suberites domuncula domuncula* (Olivi, 1792). Sublittoral, 12 to 128 m.
- S. d. ficus* (Olivi, 1792). Sublittoral, 55 to 183 m.
- S. montiniger* Carter, 1880. Sublittoral, 55 to 183 m.
- Polymastia pachymastia* de Laubenfels, 1932. Sublittoral, 6 to 274 m.
- P. pacifica* Lambe, 1894. Sublittoral, 91 to 183 m.
- Latrunculia tricineta* Hentchel, 1929. Sublittoral, 183 m.
- Tetilla villosa* (Lambe, 1894). Sublittoral, 6 to 183 m.
- T. spinosa* (Lambe, 1894). Sublittoral, 6 to 183 m.
- Corticium* sp. Sublittoral, 34 m.
- Geodinella robusta* Lendenfeld, 1910. Sublittoral, 274 m.
- Asbestopluma lycopodium* (Levinsen, 1886). Sublittoral, 91 m.
- Axinella* sp. A. Sublittoral, 183 m.
- Syringella amphispicula* de Laubenfels, 1961. Sublittoral, 183 m.
- Phylum Coclenterata
- Class Hydrozoa (Fraser, 1937).
- Order Hydroida
- Syncoryne* sp. *Laminaria* community; f, 1.0; c, 0.06; a, 1.
- Sertularella pinnata* Clark, 1876. *Laminaria* community; f, 1.0; c, 0.06; a, 1.
- Order Stylasterina
- ?*Allopora campyleca* (Fisher, 1938). Sublittoral, 183 m.
- Class Anthozoa
- Order Pennatulacea
- Ptilosarcus* sp. Subtidal, 30 to 35 m. One very young specimen collected in *Laminaria* community at IA-2.
- Order Actiniaria (All anemones were identified by K. Sebens except *Metridium* sp.)
- Family Actiniidae
- Cnidopus ritteri* (Torrey, 1902). *Laminaria* community.
- Epiactis* sp. *Laminaria* community. Several specimens bearing young.
- Tealia* sp. *Laminaria* community.
- Unidentified sp. B. *Laminaria* community; the most common anemone in the lower midlittoral zone and infralittoral fringe.
- Unidentified sp. C. *Laminaria* community.
- Unidentified sp. D. *Laminaria* community.
- Family Hormathiidae
- Unidentified sp. A. *Laminaria* community.
- Family Metridiidae
- Metridium* sp. Subtidal.
- Phylum Platyhelminthes
- Class Turbellaria (All Turbellaria identified by S. Prudhoe.)
- Order Alloeocoela
- Plagiostomidae sp. *Halosaccion-Fucus* community; f, 0.66; c, 0.18; a, 1, 1-2.
- Order Tricladida
- Nexilis epichitonius* Holleman and Hand, 1962. *Alaria-Hedophyllum* community; f, 0.6; c, 0.25, a, 9, 2-133. Not previously recorded northwest of Vancouver Island, British Columbia (Ball, 1974).
- Nesion arcticum* Hyman, 1956. Upper communities; f, 1.0; c, 0.09; a, 2.

Order Polycladida

Notoplana atomata (O. F. Müller, 1776). *Alaria-Hedophyllum* community; f. 1.0; c. 0.08; a. 1.

?*Leptoplana vesiculata* Hyman, 1939. Juvenile. *Laminaria* community; f. 1.0; c. 0.33; a. 1.

Phylum Nemertea

Class Enopla

Tetrastemma sp. Identification to genus by E.N. Kozloff of specimens collected by J. F. Palmisano.

Phylum Nematoda

Unidentified species. In the intertidal area, nematodes were most numerous among the holdfasts of *Laminaria longipes* and *Alaria crispa*, reaching densities as high as 261 per 0.062 m².

Phylum Annelida

Class Polychaeta

Harmothoe imbricata (Linnaeus, 1767). Collected and identified by K. Kimura.

Lepidonotus helotypus (Grube, 1877). Identified by R. M. O'Clair. Sublittoral, 183 m.

Pholoe minuta (Fabricius, 1780). Verified by R. M. O'Clair. *Laminaria* community; f. 0.8, c. 0.33, a. 50, 22-123.

Dysponetus pygmaeus Levinsen, 1879; Ushakov, 1955. *Laminaria* community; f. 0.8, c. 0.33, a. 50, 11-88. Arctic-boreal.

Euphrosine borealis Oersted, 1843. Identified by R. M. O'Clair. Sublittoral, 34 m.

Eteone flava (Fabricius, 1780). Identified by R. M. O'Clair. *Laminaria* community; f. 0.8, c. 0.33, a. 40, 23-56.

Eulalia (Eulalia) viridis (Linnaeus, 1767). *Laminaria* community. Widely distributed.

Eulalia (Eumida) longicornuta Moore, 1906. (Banse and Hobson, 1974). *Alaria-Hedophyllum* community. North American.

Notophyllum sp. Identified to genus by R. M. O'Clair. Sublittoral, 64 m.

Phyllodocidae sp. *Laminaria* community; f. 0.57, c. 0.33, a. 1.

Autolytus prismaticus (Fabricius, 1780). Identified by R. M. O'Clair. *Halosaccion-Fucus* community.

Autolytus beringianus Annenkova, 1934; Ushakov, 1955. *Laminaria*

community; f. 1.0, c. 0.33, a. 2. Asiatic.

Autolytus sp. *Alaria-Hedophyllum* community; f. 0.66, c. 0.17, a. 6, 1-11.

Exogone gemmifera Pagenstecher, 1862. Identified by R. M. O'Clair. Lower communities; f. 0.36; c. 0.33, a. 127, 46-889.

Sphaerosyllis sp. A. cf. *S. pirifera* Claparède, 1868. *Laminaria* community; f. 0.8, c. 0.33, a. 5, 1-9.

Sphaerosyllis sp. B. *Alaria-Hedophyllum* community; f. 0.66, c. 0.17, a. 54, 1-64.

?*Syllis (Typosyllis) alternata* Moore, 1908; Banse and Hobson, 1974. Upper communities; f. 0.5, c. 0.09, a. 202, 24-380.

Syllis (Typosyllis) armillaris (O. F. Müller, 1776). Identified by R. M. O'Clair. Lower Communities; f. 0.5, c. 0.4, a. 30, 5-318. Widely distributed.

Syllis (Typosyllis) stewarti Berkeley, 1942. Verified by R. M. O'Clair. *Halosaccion-Fucus* community; f. 1.0, c. 0.09, a. 2.

Syllis (Typosyllis) sp. Verified to subgenus by K. Banse. *Laminaria* community; f. 0.52, c. 1.0, a. 90, 9-668.

Trypanosyllis gemmipara Johnson, 1901. Identified by R. M. O'Clair. Sublittoral, 34 m. The specimen examined is 315 mm long and 5 mm wide with 596 setigers. To my knowledge it is the largest recorded specimen of this species. Deposited in NMNS.

Nereis pelagica Linnaeus, 1758. Identified by R. M. O'Clair. *Laminaria* community; f. 0.42, c. 0.47, a. 4, 1-62, and sublittoral to 183 m.

Nereis vexillosa Grube, 1851. Identified by R. M. O'Clair. Collected by K. Kimura. Intertidal. Arctic-boreal.

Nephtys sp. Identification to genus by R. M. O'Clair. Sublittoral, 183 m.

Sphaerodoropsis sp., near *S. minuta* (Webster and Benedict, 1887). Lower communities; f. 0.35, c. 0.67, a. 62, 2-381.

Eunice kobeensis McIntosh, 1885. Identified by R. M. O'Clair. Sublittoral, 6 to 270 m (see Gustus, 1972).

- Lumbrineris inflata* Moore, 1911. Identified by R. M. O'Clair. *Laminaria* community. See Table 2 for population statistics. Widely distributed.
- Naineris quadricuspida* (Fabricius, 1780). Identified by R. M. O'Clair. *Laminaria* community; f. 0.44, c. 0.33, a. 37, 25-454. Arctic-boreal.
- Polydora* sp. (see Hobson and Banse, in preparation). *Laminaria* community; f. 0.66, c. 0.33, a. 38, 23-117.
- Boccardia proboscidea* Hartman, 1940. Identified by R. M. O'Clair. *Alaria-Hedophyllum* community; f. 1.0, c. 0.08, a. 1. North American.
- Pygospio elegans* Claparède, 1863. Identified by R. M. O'Clair. *Alaria-Hedophyllum* community; f. 0.6, c. 0.25, a. 212, 54-508. Widely distributed.
- Spio filicornis* (O. F. Müller, 1776). Identified by R. M. O'Clair. Upper communities; f. 0.5, c. 0.09, a. 20, 1-38. Widely distributed.
- Chaetopterus variopedatus* (Renier, 1804). Identified by R. M. O'Clair. Sublittoral; 2 to 183 m.
- Caulleriella alata maculata* (Annenkova, 1934). Verified by R. M. O'Clair. See Table 2 for population statistics.
- Chaetozone* sp., near *C. berkeleyorum* Banse and Hobson, 1968. Upper communities; f. 0.5, c. 0.09, a. 212, 169-254.
- ?*Cirratulus cirratus spectabilis* (Kinberg, 1866) (Hartman, 1969). *Laminaria* community; f. 1.0, c. 0.06, a. 20. North American.
- Cirratulus* Type I. Determination by O. Hartman. Near *C. c. spectabilis*. Acicular uncini present from the first notopodia and neuropodia; body short with about 40 setigers (O. Hartman, personal communication). *Alaria-Hedophyllum* community.
- Cirratulus* Type II. Determination by O. Hartman. Near *C. c. spectabilis*. Acicular uncini present from first notopodia and neuropodia; body long with 50 setigers (O. Hartman, personal communication). *Halosaccion-Fucus* community. See Table 4 for population statistics.
- Cirratulus* Type III. Determination by O. Hartman. Acicular uncini present from first neuropodia and from twelfth notopodia; body as in *C. Type I* (O. Hartman, personal communication). *Alaria-Hedophyllum* community; f. 0.38, c. 0.42, a. 54, 1-762.
- Cirratulus* Type IV. Acicular uncini present from first notopodia and from sixth to eighth neuropodia; tentacular cirri similar to *C. c. spectabilis*. Included with *C. Type III* in Figs. 6 and 12. *Laminaria* community; f. 0.5, c. 0.33, a. 1, 1-23.
- Cirratulus* sp. *Alaria-Hedophyllum* community; f. 1.0, c. 0.08, a. 4.
- Cirratulidae* sp. Upper communities; f. 0.5, c. 0.09, a. 96, 64-127.
- Brada granulata* Malmgren, 1867. Identified by R. M. O'Clair. Sublittoral; 183 m.
- Flabelligera infundibularis* Johnson, 1901. Identified by R. M. O'Clair. *Laminaria* community. North American.
- Scalibregma inflatum* Rathke, 1843. Identified by R. M. O'Clair. *Laminaria* community.
- Capitella capitata* (Fabricius, 1780). Identified by R. M. O'Clair. *Alaria-Hedophyllum* community; f. 0.38, c. 0.42, a. 127, 1-444.
- Abarenicola claparedii oceanica* Healy and Wells, 1959. Verified by R. M. O'Clair. Intertidal in moat (see Fig. 3 in Lebednik and Palmisano, Chap. 17, this volume). North Pacific.
- Praxillella praetermissa* (Malmgren, 1866). Identified by R. M. O'Clair. Sublittoral, 34 m.
- Idanthyrus armatus* Kinberg, 1867. Identified by R. M. O'Clair. Sublittoral, 55 m.
- Asabellides sibirica* (Wirén, 1883) [= *Pseudosabellides littoralis* Berkeley and Berkeley, 1943] (see Hartman, 1959, p. 492). *Laminaria* community; f. 0.57, c. 0.33, a. 38, 38-276.
- Amphiglena pacifica* Annenkova, 1934. Identified by R. M. O'Clair. Upper communities; f. 0.5, c. 0.56, a. 127, 27-1562. Endemic. The type locality of *A. pacifica* is Bering Island, not Bering Strait as listed in Hartman (1959).
- Chone cincta* Zachs, 1933. Identified by R. M. O'Clair. *Alaria-Hedophyllum* community; f. 0.46, c. 0.83, a. 190, 4-1544. Asiatic.

C. infundibuliformis Krøyer, 1856. Identified by R. M. O'Clair. Sublittoral, 34 m.

Demonax? sp. *Laminaria* community. See Table 2 for population statistics.

Fabricia sabella (Ehrenberg, 1836). Identified by R. M. O'Clair. *Alaria-Hedophyllum* community; f. 0.41, c. 0.58, a. 3594, 23-29, 274.

Myxicola infundibulum (Renier, 1804). Identified by R. M. O'Clair. Sublittoral, 34 m.

Potamilla reniformis (Leuckart, 1849). Identified by R. M. O'Clair. Sublittoral, 34 m.

Sabella crassicornis Sars, 1851. Identified by R. M. O'Clair. Sublittoral, 34 m.

Dexiospira semidentata (Bush, 1904). Identified by R. M. O'Clair. *Laminaria* community; f. 0.66, c. 0.33, a. 1, 1-24. North Pacific.

Dexiospira sp. *Laminaria* community; f. 0.62, c. 0.67, a. 32, 11-6632.

Class Oligochaeta (All Oligochaeta identified by D. G. Cook.)

Paranaïs littoralis (Müller, 1784). *Halosaccion-Fucus* community. See Table 4 for population statistics.

Tubificidae sp. Immature specimens. *Laminaria* community; f. 0.57, c. 0.67, a. 38, 1-124.

Lumbricillus sp. *Alaria-Hedophyllum* community. See Table 3 for population statistics.

Phylum Mollusca (Oldroyd, 1924-1927).

Class Gastropoda [The nomenclature of species of the superfamilies Patellacea and Fissurellacea generally follows McLean (1966; 1969)].

Problacmaea sybaritica (Dall, 1871) [= *Acmaea* (*Tectura*) *sybaritica* Dall, 1871]. Identified by A. M. Keen. Golikov and Kussakin (1972) include this species in the genus *Problacmaea* because it is ovoviviparous. Two specimens collected in August 1968 had been brooding young (520 individuals in one adult) dorsally beneath the wall of the visceral mass. *Laminaria* community; f. 0.6, c. 0.06, a. 1, 1-3. Asiatic.

Collisella pelta (Rathke, 1833). *Alaria-Hedophyllum* community; f. 0.4, c. 0.43, a. 2, 1-31. North Pacific.

Collisella digitalis (Rathke, 1833).

Halosaccion-Fucus community. See Table 4 for population statistics. North American.

Collisella strigatella (Carpenter, 1864). Verified by J. H. McLean. *Halosaccion-Fucus* community; f. 0.59, c. 0.36, a. 4, 1-36. North American.

Notoacmea scutum (Rathke, 1833). *Laminaria* community. See Table 2 for population statistics. North Pacific.

Rhodopetala rosea (Dall, 1872) (= *Nacella rosea* Dall, 1872). Verified by J. H. McLean. This species was usually found on the holdfasts and fronds of *Laminaria yezoensis*. One specimen collected in May 1974 was brooding young (404 individuals) in its nuchal cavity. Other adults in the vicinity of this specimen at the time of collection were surrounded by many tiny, apparently newly released, limpets. Asiatic.

Diadora sp. Sublittoral, 6 m.

Puncturella (*Puncturella*) *noachina* (Linnaeus, 1771). [= *P. longifissa* Dall, 1914.] Verified by J. H. McLean. *Laminaria* community. Arctic-boreal.

Margarites beringensis (Smith, 1899). [= *M. helacinus excavatus* Dall, 1919. J. H. McLean (personal communication).] *Laminaria* community; f. 0.46, c. 0.6, a. 4, 1-468. Arctic-boreal.

M. vorticifera (Dall, 1873). Identified by J. H. McLean. *Laminaria* community.

Moelleria quadrae Dall, 1897. Verified by J. H. McLean. *Laminaria* community. North American.

Balcis randolphi (Vanatta, 1899). Verified by A. M. Keen. *Laminaria* community; f. 0.53, c. 0.67, a. 2, 1-188. North Pacific.

Littorina aleutica Dall, 1872. Verified by A. M. Keen. *Halosaccion-Fucus* community. See Table 4 for population statistics. Endemic.

L. atkana Dall, 1886. Verified by A. M. Keen. *Halosaccion-Fucus* community. See Table 4 for population statistics. North American.

L. sithkana Philippi, 1845. Verified by A. M. Keen. *Halosaccion-Fucus* com-

- munity. See Table 4 for population statistics. North Pacific.
- Haloconcha minor* Dall, 1919. Identified by A. M. Keen. *Halosaccion-Fucus* community; f. 0.38, c. 0.7, a. 9, 1-368. North Pacific.
- Alvinia castanella* (Dall, 1886). Verified by J. H. McLean. *Laminaria* community. Endemic.
- A. aurivillii* (Dall, 1886). Verified by A. M. Keen. *Laminaria* community; f. 0.57, c. 0.67, a. 1, 1-306. Asiatic.
- Cingula aleutica* Dall, 1886. Compared with USNM specimens. *Halosaccion-Fucus* community; f. 0.46, c. 0.82, a. 602, 2-2032. North Pacific.
- Cingula martyni* Dall, 1886. Identified by A. M. Keen. *Halosaccion-Fucus* community; f. 0.57, c. 0.64, a. 234, 2-3810. Arctic-boreal.
- Rissoidae sp. A. Verified to family by J. H. McLean. Lower intertidal communities.
- Rissoidae sp. B. Verified to family by J. H. McLean. *Laminaria* community; f. 0.62, c. 0.67, a. 4, 2-62.
- Vitrinella* sp. Verified to genus by J. H. McLean. *Alaria-Hedophyllum* community. See Table 3 for population statistics.
- Cerithiopsis* sp. cf. *C. stephensae* Bartsch, 1909. Determination by A. M. Keen. *Alaria-Hedophyllum* community. North American.
- Cerithiopsis stejneri* Dall, 1884. Compared with USNM specimens. *Alaria-Hedophyllum* community. See Table 3 for population statistics. Asiatic.
- Natica clausa* Broderip and Sowerby, 1829. *Laminaria* community; f. 0.86, c. 0.13, a. 1, 1-2.
- Polinices* sp. Indeterminate juveniles. Identified to genus by A. M. Keen. Upper communities.
- Velutina conica* Dall, 1886. Compared with USNM specimens. *Laminaria* community. North Pacific.
- Fusitriton oregonensis* (Redfield, 1848). Sublittoral, 6 to 30 m.
- Trophonopsis* (= *Boreotrophon*) sp. Sublittoral, 18 to 38 m.
- Thais lima* (Martyn, 1784). *Alaria-Hedophyllum* community; f. 0.48, c. 0.52, a. 4, 1-16. North Pacific.
- Buccinum baeri morchianum* Fischer, 1858. Identified by A. M. Keen. *Laminaria* community; f. 0.56, c. 0.47, a. 3, 1-8. North Pacific.
- Mitrella amiantis* (Dall, 1919). Identified by A. M. Keen. *Laminaria* community. See Table 2 for population statistics. Endemic.
- ?*Arctomelon stearnsii* Dall, 1872. Sublittoral, 183 m. Collected by J. S. Isakson.
- Antiplanes* sp. Sublittoral, 91 m.
- Suavodrillia kennicottii* (Dall, 1871). Identified by R. Shimek. Shell containing hermit crab. Collected by J. S. Isakson and P. N. Slattery. Sublittoral.
- Odostomia krausei* Clessin, 1900. Identified by A. M. Keen. *Laminaria* community; f. 0.5, c. 0.33, a. 2, 1-49. North Pacific.
- Diaphana brunnea* Dall, 1919. Identified by J. H. McLean. One specimen collected in an area uplifted from the sublittoral by Cannikin. North American.
- Philine* sp. Verified to genus by J. H. McLean. *Laminaria* community; f. 1.0, c. 0.33, a. 1.
- Diaulula sandiegensis* (Cooper, 1862). Identified by G. Robilliard from photographs taken by Auke Bay, Alaska, Fisheries Laboratory personnel (L. Barr, personal communication). Sublittoral. North Pacific.
- Triopha carpenteri* (Stearns, 1873). Identified by G. Robilliard from photographs taken by Auke Bay, Alaska, Fisheries Laboratory personnel (L. Barr, personal communication). Sublittoral. North Pacific.
- ?*Polyceratidae* sp. Juvenile. *Laminaria* community.
- Tritonia* sp. Sublittoral, 91 m.
- Aeolidia*? sp. *Laminaria* community.
- Siphonaria thersites* Carpenter, 1864. Verified by A. M. Keen. *Halosaccion-Fucus* community. See Table 4 for population statistics. North American.
- Onchidella borealis* Dall, 1871. Compared with USNM specimens. *Alaria-Hedophyllum* community. North American.

Class Amphineura

- Cryptochiton stelleri* (Middendorff, 1846). Shell plates found by L. Sowl.
- Lepidochitona aleuticus* Dall, 1878. Compared with USNM specimens.

Lower communities; f. 0.41, c. 1.0, a. 45, 1-296. Asiatic.

Katharina tunicata (Wood, 1815). *Alaria-Hedophyllum* community. See Table 3 for population statistics. North Pacific.

Amicula sp. Subtidal, 37 m.

Mopalia sp. Sublittoral, 3 m.

Placiphorella sp. Subtidal, 5 to 24 m.

Schizoplax brandtii (Middendorff, 1846). *Alaria-Hedophyllum* community; f. 0.45, c. 0.36, a. 3, 1-42. North Pacific.

Hanleya ? sp. *Laminaria* community.

Class Bivalvia

Modiolus modiolus (Linnaeus, 1758) (Soot-Ryen, 1955). Sublittoral.

Musculus discors var. *laevigatus* (Gray, 1824). Identified by A. M. Keen. *Laminaria* community.

?*M. d.* var. *laevigatus* f. *substriatus* (Gray, 1824) (MacGinitie, 1959). *Laminaria* community; f. 0.61, c. 0.2, a. 1, 1-4.

Musculus vernicosus (Middendorff, 1849). Verified by A. M. Keen. *Laminaria* community; f. 0.46, c. 0.2, a. 2, 1-9. Also sublittoral to 12 m. Arctic-boreal.

Mytilus edulis Linnaeus, 1758 (Soot-Ryen, 1955). Large individuals, *Alaria-Hedophyllum* community. See Table 3 for population statistics. Small individuals, *Alaria-Hedophyllum* community; f. 0.47, c. 0.36, a. 62, 1-6200.

M. californianus Conrad, 1837 (Soot-Ryen, 1955). A single specimen found on Amchitka collected by J. F. Palmisano. North American.

Pododesmus macroschisma (Deshayes, 1839). Sublittoral, 12 m. North Pacific.

Kellia suborbicularis (Montagu, 1803). Compared with NMNS specimens. *Laminaria* community. Widely distributed.

Mysella aleutica (Dall, 1899). Identified by A. M. Keen. *Halosaccion-Fucus* community. See Table 4 for population statistics.

Turtonia minuta (Fabricius, 1780). Identified by A. M. Keen. *Laminaria* community; f. 0.35, c. 1.0, a. 252, 1-28,130. Arctic-boreal. Though widely distributed in the intertidal area at Amchitka, this little clam is

most abundant in the upper communities. It appears to be ecologically similar to *Lasaea cistula* Keen (see Glynn, 1965). *Turtonia minuta* is similar in size and morphology to *L. cistula*. Both species are nestlers, although *T. minuta* appears to prefer areas of high siltation. Both species brood their young.

Serripes groenlandicus (Bruguère, 1789). Sublittoral. Shell only.

Spisula polynyma (Stimpson, 1860). Sublittoral. Arctic-boreal.

?*Siliqua media* Sowerby, 1839 [= *S. alta*? (Broderip and Sowerby, 1829) (Abbott, 1974)]. Shell only. Sublittoral.

Macoma calcarea (Gmelin, 1791). Identified by A. M. Keen. *Alaria-Hedophyllum* community. See Table 3 for population statistics.

M. obliqua (Sowerby, 1817) (Coan, 1971). Intertidal. North American.

Hiatella arctica (Linnaeus, 1767). *Laminaria* community; f. 0.75, c. 0.06, a. 4, 1-7. Also sublittoral to 210 m.

Class Cephalopoda [All cephalopods (except *Japetella*) collected and identified by G. J. Tutmark.]

Gonatus magister Berry, 1913. Pelagic. *G. fabricii* (Lichtenstein, 1818). Pelagic.

Gonatopsis borealis Sasaki, 1923. Pelagic.

Galiteuthis armata Joubin, 1898. Pelagic.

Chiroteuthis veranyi (Férussac, 1835). Pelagic.

Architeuthis princeps Verrill, 1875. Pelagic.

Octopus ? sp. Intertidal to 30 m.

Japetella heathi (Berry, 1911). Identified by M. Green.

Phylum Arthropoda

Class Arachnida

Order Acarina

Family Bdellidae

Neomolgus littoralis (Linnaeus, 1758). Identified by E. E. Lindquist. Supralittoral zone.

Family Parasitidae

Parasitus sp. Identified to genus by E. E. Lindquist. Supralittoral zone.

Class Pycnogonida (All Pycnogonida identified by G. W. O'Connell.)

- Pseudopallene circularis* (Goodsir, 1842). Subtidal, 24 to 30 m.
Phoxichilidium femoratum (Rathke, 1799). Subtidal, 6 to 183 m.
Achelia latifrons (Cole, 1904). *Laminaria* community.
A. pribilofensis (Cole, 1904). Lower intertidal communities.
A. alaskensis (Cole, 1904). *Laminaria* community.
A. sp. 1. *Laminaria* community.
A. sp. 2. Subtidal, 24 m.
A. sp. 4. Subtidal, 12 m.
Colossendeis orientalis Losina-Losinsky, 1958. Subtidal, 274 m.
Rhopalorhynchus chitinosum (Hilton, 1943). Subtidal, 183 m.
Pycnogonum crassirostre Sars, 1888. *Laminaria* community to 24 m.
Pycnogonum cf. P. ungellatum Loman, 1911. Subtidal, 183 m.

Class Crustacea

Subclass Copepoda

Order Harpacticoida

Unidentified species. Nearly all individuals passed through the 1-mm sieve.

Order Notodelphyoida

Blakeanus corniger Wilson, 1921. Identified by P. L. Illg. In the branchial basket of Styelidae sp. Lower communities.

Subclass Cirripedia

Balanus cariosus (Pallas, 1788) (Pilsbry, 1916). *Alaria-Hedophyllum* community. See Table 3 for population statistics. North Pacific.

B. glandula Darwin, 1854; Pilsbry, 1916. *Halosaccion-Fucus* community; f. 0.64, c. 0.17, a. 3, 1-1760. North American.

Lepas anatifera (Linnaeus, 1758). On debris washed ashore.

Subclass Malacostraca

Order Nebaliacea

Nebalia sp. *Laminaria* community.

Order Mysidacea

Gnathophausia gigas Willemoes-Suhm, 1875. Identified by G. J. Tutmark. Pelagic.

Paracanthomysis kurilensis Ii, 1936. Identification by C. Holmquist of specimens collected by P. N. Slattery. Neritic.

Order Tanaidacea

Tanais alascensis Richardson, 1899. Identified by G. J. Tutmark. Sublittoral. Endemic.

Anatanais ? sp. Lower communities.

Tanaidae sp. *Alaria-Hedophyllum* community; f. 1.0, c. 0.08, a. 1.

Order Isopoda (Richardson, 1905) (Schultz, 1969).

Limnoria lignorum Rathke, 1799. See Richards and Belmore (1976) for collection data.

Exosphaeroma amplicauda (Stimpson, 1857). *Alaria-Hedophyllum* community; f. 0.39, c. 0.82, a. 4, 1-96. North American.

Gnorimosphaeroma oregonensis (Dana, 1855). *Halosaccion-Fucus* community; f. 0.83, c. 0.09, a. 1, 1-5. North Pacific.

Dynamenella sheareri (Hatch, 1947). *Alaria-Hedophyllum* community; f. 0.43, c. 0.5, a. 310, 32-1026. North American.

?*Arcturus longispinus* (Benedict, 1898). Sublittoral, 183 m.

Idotea (Idotea) ochotensis Brandt, 1851. Verified by F. Rafi. *Laminaria* community. North Pacific.

Idotea (Pentidotea) wosnesenskii (Brandt, 1851). Verified by F. Rafi. *Alaria-Hedophyllum* community; f. 0.36, c. 0.84, a. 6, 1-74. North American.

Ianiropsis kincaidi derjugini Gurjanova, 1933 (Menzies, 1952). *Laminaria* community. North Pacific. Females collected in October 1971 were carrying eggs and young.

Ligia pallasii Brandt, 1833. Supralittoral fringe. North American.

Munna (Neomunna) stephenseni Gurjanova, 1933. *Laminaria* community; f. 0.8, c. 0.33, a. 2, 1-2. North Pacific.

?*Munna subneglecta* Gurjanova, 1936. *Laminaria* community; f. 0.8, c. 0.33, a. 44, 1-88. Asiatic.

Munna sp. c.f. *M. (Neomunna) arnholdi* Gurjanova, 1933. *Laminaria* community; f. 1.0, c. 0.33, a. 1.

Order Amphipoda

Odius sp. *Laminaria* community; f. 0.8, c. 0.67, a. 1.

Amphithoe sp. *Alaria-Hedophyllum* community; f. 0.38, c. 0.75, a. 42, 1-500.

- Calliopiella* sp.A. Collected by P. N. Slattery. An undescribed species (Slattery, unpublished manuscript).
- Calliopiella* sp.B. Collected by P. N. Slattery. An undescribed species (Slattery, unpublished manuscript).
- Calliopiella* sp.C. Collected by P. N. Slattery. An undescribed species (Slattery, unpublished manuscript).
- Calliopiella* ? sp. *Halosaccion*-*Fucus* community. See Table 4 for population statistics.
- Calliopiidae Type I. *Halosaccion*-*Fucus* community.
- Calliopiidae Type II. *Halosaccion*-*Fucus* community; f. 1.0, c. 0.09, a. 1.
- Calliopiidae Type III. *Alaria*-*Hedophyllum* community; f. 1.0, c. 0.08, a. 1.
- Corophium brevis* Shoemaker, 1949. Identified by U. Lie. *Alaria*-*Hedophyllum* community. See Table 3 for population statistics. North American.
- Pontogeneia andrijaschevi* Gurjanova, 1951. Tentative identification by E. L. Bousfield of specimens collected by P. N. Slattery (Slattery, unpublished manuscript). Asiatic.
- P. ivanovi* Gurjanova, 1951. Tentative identification by E. L. Bousfield of specimens collected by P. N. Slattery (Slattery, unpublished manuscript). Asiatic.
- ?*P. intermedia* Gurjanova, 1938 (Gurjanova, 1951). In pool on uplifted rock bench, probably stranded in a storm. North Pacific.
- P. makarovi* Gurjanova, 1951. Identification by E. L. Bousfield of specimens collected by P. N. Slattery. *Laminaria* community; f. 0.47, c. 0.27, a. 4, 1-69. Asiatic.
- P. rostrata* Gurjanova, 1938. Identified by P. N. Slattery and confirmed by W. S. Gray. North Pacific.
- Pontogeneia* sp. Confirmed to genus by P. N. Slattery. *Laminaria* community; f. 0.65, c. 0.2, a. 2, 1-8.
- Eusiridae sp. *Halosaccion*-*Fucus* community; f. 1.0, c. 0.02, a. 1.
- Anisogammarus confervicolus* (Stimpson, 1857). Identified by U. Lie. *Alaria*-*Hedophyllum* community.
- See Table 3 for population statistics. North American.
- Allorchestes* sp. Near *A. carinata* Iwasa, 1939. Mature males unavailable for study. *Laminaria* community; f. 0.6, c. 0.06, a. 1, 1-2.
- Parallorchestes ochotensis* (Brandt, 1851) (Barnard, 1962). *Laminaria* community; f. 0.49, c. 0.67, a. 8, 1-137. North Pacific.
- Ischyrocerus* Type I. Verified to genus by U. Lie. Lower communities; f. 0.5, c. 0.2, a. 2, 1-10.
- Ischyrocerus* Type II. *Laminaria* community; f. 0.66, c. 0.33, a. 2, 1-3.
- Jassa* sp. Verified to genus by U. Lie. *Laminaria* community; f. 0.66, c. 0.33, a. 16, 1-32.
- Orchomene* ? sp. *Laminaria* community; f. 0.5, c. 0.67, a. 100, 1-318.
- Paraphoxus spinosus* Holmes, 1903 (Barnard, 1960). *Alaria*-*Hedophyllum* community; f. 0.46, c. 0.42, a. 106, 13-381. Amphiboreal.
- Parapleustes pugettensis* (Dana, 1853). Identified by U. Lie. *Laminaria* community; f. 0.57, c. 0.67, a. 2, 1-4. North American.
- Pleustes* sp. *Laminaria* community.
- Sympleustes* sp. Verified to genus by U. Lie. *Laminaria* community; f. 0.66, c. 0.33, a. 2, 1-85.
- Mesometopa* ? sp. Verified to family by E. L. Bousfield. *Laminaria* community; f. 1.0, c. 0.33, a. 1.
- Parametopella stelleri* Gurjanova, 1948. Tentatively identified by E. L. Bousfield. *Laminaria* community; f. 0.8, c. 0.33, a. 1. Asiatic.
- ?*Najna consiliorum* Derzhavin, 1937 (Bulycheva, 1957) (Barnard, 1962). Verified to genus by U. Lie. *Laminaria* community; f. 0.88, c. 0.33, a. 2, 1-3. North Pacific.
- Orchestia* sp. Supralittoral fringe.
- Caprella kincaidi* Cole, 1910. *Laminaria* community; f. 0.66, c. 0.67, a. 1, 1-19. Asiatic.
- C. laeviuscula* Mayer, 1903 (Laubitz, 1970). *Laminaria* community. North Pacific.
- Cercops compactus* Laubitz, 1970. Verified by D. Laubitz. *Laminaria* community. See Table 2 for population statistics. North American.
- Caprella* sp. *Laminaria* community; f. 1.0, c. 0.33, a. 2, 1-2.

Order Euphausiacea (All euphausiids identified by G. J. Tutmark.)

- Thysanoessa longipes* Brandt, 1851. Pelagic.
T. inermis (Krøyer, 1846). Pelagic.
Euphausia pacifica Hansen, 1911. Pelagic.
Tessarobranchion oculatum Hansen, 1911. Pelagic.

Order Decapoda

- Sergestes similis* Hansen, 1903. Identified by G. J. Tutmark. Pelagic.
Hymenodora frontalis Rathbun, 1902. Identified by G. J. Tutmark. Pelagic.
Notostomus japonicus Bate, 1888. Identified by G. J. Tutmark. Pelagic.
Pandalus montagui tridens Rathbun, 1902. Sublittoral, 55 to 183 m.
Lebbeus groenlandica (Fabricius, 1775). Sublittoral, 55 to 183 m.
Lebbeus grandimanus (Brashnikov, 1907). Identified by G. J. Tutmark. Sublittoral, 5 m.
Eualus fabricii (Krøyer, 1841). Identified by G. J. Tutmark. Sublittoral, 1 m.
Spirontocaris arcuata Rathbun, 1902. Identified by G. J. Tutmark. Sublittoral.
Nectocrangon crassa Rathbun, 1899. Sublittoral, 55 m. North Pacific. Nomenclature of pagurids follows McLaughlin (1974).
Elassochirus gilli (Benedict, 1892). Identified by G. J. Tutmark. Verified by C. Nyblade. Sublittoral.
E. tenuimanus (Dana, 1851). Identified by G. J. Tutmark. Verified by C. Nyblade. Sublittoral, 55 m.
E. cavimanus (Miers, 1879). Identified by G. J. Tutmark. Verified by C. Nyblade. Sublittoral, 55 m.
Pagurus beringanus (Benedict, 1892). Identified by C. Nyblade. Sublittoral.
P. capillatus (Benedict, 1892). Identified by G. J. Tutmark. Verified by C. Nyblade. Sublittoral.
P. dalli (Benedict, 1892). Identified by G. J. Tutmark. Verified by C. Nyblade. Sublittoral, 183 m.
P. hirsutiusculus hirsutiusculus (Dana, 1851). Identified by C. Nyblade. Intertidal.
P. kennerlyi (Stimpson, 1864). Identified by G. J. Tutmark. Verified by C. Nyblade. Sublittoral, 26 m.

- P. setosus* (Benedict, 1892). Identified by G. J. Tutmark. Sublittoral.
P. stevensae Hart, 1971. Identified by C. Nyblade. Sublittoral.
P. trigonocheirus (Stimpson, 1858). Identified by C. Nyblade. Sublittoral, 55 m.
Cryptolithodes typicus Brandt, 1849. See Barr (1973). North American.
Dermaturus mandtii Brandt, 1850 (Makarov, 1938). Intertidal to 5 m.
Hapalogaster grebnitzkii Schalfeew, 1892 (Makarov, 1938). Sublittoral, 5 m.
Lithodes aequispina Benedict, 1894 (Makarov, 1938). Sublittoral, 91 to 302 m.
Oedignathus inermis (Stimpson, 1860). Identified by G. J. Tutmark. Sublittoral. North Pacific.
Paralithodes camtschatica (Tilesius, 1815) (Makarov, 1938). Sublittoral, 18 to 192 m.
Placetrion wosnessenskii Schalfeew, 1892 (Makarov, 1938). Sublittoral, 21 to 192 m.
Rhinolithodes wosnessenskii Brandt, 1849. Collected and identified by L. Barr. Sublittoral.
Chionoecetes bairdi Rathbun, 1893 (Garth, 1958). Sublittoral, 24 to 192 m.
Oregonia gracilis Dana, 1851 (Garth, 1958). Sublittoral, 29 to 192 m.
Pugettia gracilis Dana, 1851 (Garth, 1958). Uplifted sublittoral fringe.
Erimacrus isenbeckii (Brandt, 1848). Sublittoral, 20 to 214 m.
Telmessus cheiragonus (Tilesius, 1815). Only remains of carapace found.
Cancer magister Dana, 1852. One specimen collected in gill net at a depth of 1 m.
C. oregonensis (Dana, 1852). Infralittoral fringe to -5 m.

Class Insecta

Order Coleoptera

- Liparocephalus brevipennis* Mäklin, 1853. Verified to genus by M. Hatch and to species by J. M. Campbell and E. C. Becker. *Laminaria* community; f. 0.65, c. 0.33, a. 46, 4-88.

Order Diptera

Family Chironomidae

- Saundersia marinus* (Saunders, 1928). Adults identified by D. R. Oliver;

larvae identified by M. E. Roussel. On rocky substrate uplifted into the supralittoral fringe zone by Cannikin. *Paraclunio alaskensis* (Coquillett, 1900). Adults identified by D. R. Oliver; larvae identified by M. E. Roussel. Adults in supralittoral zone; larvae in upper intertidal communities and supralittoral fringe zone.

Telmatogeton sp. (pupa). Identified to genus by M. E. Roussel. *Halosaccion-Fucus* community.

Suborder? Sciomyzoidea (Unidentified species near Family Anthomyiidae, larva. Determination by H. J. Teskey. *Halosaccion-Fucus* community.)

Order Lepidoptera

Family Geometridae

?*Dysstroma* sp. (larva). Tentative identification to genus by S. Allynson. Supralittoral zone.

Phylum Sipuncula

Phascolosoma agassizii Keferstein, 1867. Identification by A. J. Kohn of specimens collected by C. A. Simenstad. *Laminaria* community; f. 0.75, c. 0.06, a. 2, 1-2.

Phylum Echiura

Bonelliopsis alaskana Fisher, 1946 (Stephen and Edmonds, 1972). Verified to genus by A. R. Fontaine. *Laminaria* community to -14 m.

Phylum Bryozoa (All bryozoans identified by M. Dick.)

Order Ctenostomata

Flustrellidra vegae (Silcn, 1947). *Laminaria* community; f. 1.0, c. 0.06.

Order Cheilostomata

Cauloramphus sp. Sublittoral, 55 m.

Callopora sp.A. May be a geographical form of *C. horrida* (M. Dick, personal communication). Sublittoral, 55 m.

Callopora sp.B. Sublittoral, 55 m.

Bidenkapia spitsbergensis var. *alaskensis* Osburn, 1953. Sublittoral, 55 m.

Tegella sp. Sublittoral, 55 m.

Tricellaria erecta (Robertson, 1900). *Laminaria* community.

Dendrobeania murrayana (Johnson, 1847). *Laminaria* community.

D. m. var. *fruticosa* (Packard, 1863). Sublittoral, 55 m.

Dendrobeania sp. Sublittoral, 55 m.

Beania sp.A cf. *B. columbiana* O'Donoghue, 1923. Sublittoral, 55 m.

Beania sp.B. Sublittoral, 55 m.

Reginella sp. Sublittoral, 55 m.

Cribrilinidae sp. Sublittoral, 55 m.

Hippothoa hyalina (Linnaeus, 1758).

Laminaria community; f. 0.73, c. 0.4.

Rhamphostomella bilaminata (Hincks, 1877). Sublittoral, 55 m.

Myriozoum sp. May be a geographical form of *M. subgracile* d'Orbigny, 1852. (M. Dick, personal communication). Sublittoral, 55 m.

Order Cyclostomata

Fasciculipora pacifica Osburn, 1953. Sublittoral, 55 m.

Plagioecia patina (Lamarck, 1816). Sublittoral, 55 m.

Crisia sp. cf. *C. eburnea* (Linnaeus, 1758). *Laminaria* community; f. 0.69, c. 0.33.

Lichenopora sp. Sublittoral, 55 m.

Phylum Brachiopoda (All Brachiopoda identified by C. W. Thayer.)

Hemithyris psittacea (Gmelin, 1790). Subtidal, 9 to 183 m.

Laqueus vancouveriensis (Davidson, 1877). *Laminaria* community.

Phylum Echinodermata

Class Asteroidea [Asteroide nomenclature generally follows Fisher (1911; 1928; 1930)].

Order Phanerozonia

Hippasteria? sp. Sublittoral, 128 m.

Order Spinulosa

Crossaster papposus (Linnaeus, 1767) (Fisher, 1911). Sublittoral, 18 to 55 m.

Peribolaster biserialis (Fisher, 1905). Identified by M. E. Downey, Subtidal, 24 m.

Diplopteraster multipes (Sars, 1865) (Fisher, 1911). Sublittoral, 192 m.

Pteraster sp. Sublittoral, 6 to 12 m.

Aleutiaster schefferi (Clark, 1939). Identified by M. E. Downey. *Laminaria* community; f. 0.72, c. 0.4, a. 1, 1-9. Specimens deposited in the USNM and the British Museum (Natural History).

Henricia tumida Verrill, 1909 (D'yakonov, 1950). *Laminaria* community; f. 0.64, c. 0.27, a. 1, 1-4.

H. leviuscula (Stimpson, 1857) (Fisher, 1911). *Laminaria* community; f. 1.0, c. 0.06, a. 1.

Order Forcipulata

Leptasterias alaskensis (Verrill, 1909) (Fisher, 1930). *Laminaria* community; f. 0.75, c. 0.06, a. 2, 1-2.

L. aleutica (Fisher, 1930). *Laminaria* community. See Table 2 for population statistics. I could not distinguish small *L. alaskensis* from *L. aleutica* without examining the pedicellariae. These two species were not distinguished in field observations; however, *Leptasterias* in random samples from the intertidal area were mostly *L. aleutica*.

Class Ophiuroidea

Gorgonocephalus caryi (Lyman, 1860) (Clark, 1911). Sublittoral, 128 m.

?*Amphipholis squamata* (Delle Chiaje, 1828) (Clark, 1911; D'yakonov, 1954.) Sublittoral, 34 m.

Amphipholis sp. Sublittoral, 18 m.

Amphiura sp. Sublittoral, 12 to 18 m.

Ophiopholis aculeata (Linnaeus, 1767) (Clark, 1911) (D'yakonov, 1954). *Laminaria* community; f. 1.0, c. 0.06, a. 2. Also sublittoral to 274 m.

Ophiura maculata (Ludwig, 1886) (Clark, 1911) (D'yakonov, 1954). Infralittoral fringe to 37 m.

O. sarsii (Lütken, 1854) (Clark, 1911). Sublittoral, 91 m.

Ophiura sp. Sublittoral, 18 m.

?*Ophiacantha enneactis* Clark, 1911. Some specimens have characters nearer *O. nutrix* Baranova, 1954. The number of arms is variable. Several specimens were brooding young, which to my knowledge is the first record of brooding in this species. Sublittoral, 183 m.

Class Echinoidea

Strongylocentrotus polyacanthus Agassiz and Clark, 1907. Specimens examined were identified primarily on the basis of the size of the

endtooth of globiferous pedicellariae and the shape of the valves of the ophicephalus pedicellariae (see Mortensen, 1943). Specimens collected subtidally at Amchitka by NMFS biologists from Auke Bay, Alaska, have been tentatively identified as *S. polyacanthus* by D. L. Pawson (L. Barr, personal communication). M. Jensen verified several intertidal specimens. *Laminaria* community. See Table 2 for population statistics. Also sublittoral to 35 m.

Dendraster ? sp. Sublittoral.

Class Holothuroidea

Cucumaria vegae (Théel, 1886). Verified by D. L. Pawson. *Alaria-Hedophyllum* community; f. 0.41, c. 0.92, a. 212, 1-4128.

Psolus sp. Sublittoral, 183 m.

Phylum Chordata

Class Ascidiacea

Styela clavata (Pallas, 1774). Identified by D. P. Abbott. *Laminaria* community; f. 1.0, c. 0.13, a. 2, 1-2. Also sublittoral to 12 m.

?*S. coriacea* (Alder and Hancock, 1848) (Van Name, 1945). *Laminaria* community; f. 0.88, c. 0.33, a. 8, 6-82.

Styela ? sp. (Van Name, 1945). *Laminaria* community; f. 0.57, c. 0.27, a. 23, 1-218.

Aplidium Type I (Van Name, 1945). *Laminaria* community; f. 0.82, c. 0.2, a. 1, 1-7 colonies.

Aplidium Type II. Near *A. translucidum* Ritter, 1901 (Van Name, 1945). *Laminaria* community; f. 1.0, c. 0.06, a. 1 colony.

Suborder Aplousobranchia

Unidentified species (Van Name, 1945). *Laminaria* community; f. 0.67, c. 0.13, a. 1, 1-4 colonies.

Marine Fish Communities*

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Intensive multiple-gear sampling of the fish fauna occupying the marine waters adjacent to Amchitka Island showed 92 fish species distributed over seven basic communities according to their characteristic habitats—littoral, inshore/rock—algae, inshore/sand—gravel, offshore demersal/rock—sponge, offshore demersal/sand—gravel, epipelagic, and mesopelagic. Recurrent group analysis disclosed 13 statistically distinct species associations within five of these communities as well as several distinct predator—prey relationships. North American species predominated in the composition of the fish fauna, which reflects the principal dispersal role of the Alaska Stream current, which flows westward about Amchitka. Benthic pelagic amphipods and mysids are the predominant prey organisms, and both serve

a major role in the transfer of algae-based detritus to the inshore fish communities; euphausiids contribute similarly to offshore fish communities. The Pacific sand lance appears to be a significant importer of offshore-derived zooplankton biomass into the inshore fish communities. Among the three underground nuclear tests at Amchitka, Cannikin produced the most significant impact by kills of several fish species and changes in habitat through uplifting of some littoral rock benches. Although the recovery of the affected fish communities appeared to be complete within a year, the habitat and prey resources formerly provided by the bench that is now uplifted will remain unavailable for many years.

The Aleutian archipelago occupies a distinctive zoogeographic position as a shallow-water bridge joining temperate Asia and North America. As a result the assemblages of marine fishes inhabiting the waters adjacent to Amchitka Island are distinct within ichthyofauna of the North Pacific and within that of the Aleutian Islands of Alaska. Although deepwater species common to the Aleutians are distributed throughout the North Pacific basin, the Aleutian fish fauna of nearshore and intertidal waters is characterized predominantly by North American forms. This predominance appears to be due to the Alaska Stream, the nearshore westward-flowing surface current that originates in the Gulf of Alaska and eventually loses its distinctness as it is diverted north and east through the major passes in the western portion of the chain (Fig. 1, Chap. 16). The Alaska Stream, rather than the eastward-flowing subarctic Kuroshio (Japanese) current much farther to the south, is primary in dispersing the pelagic eggs, larvae, and juveniles of indigenous species. Willimovsky (1964) called this mechanism of westward dispersal a "filter bridge" in that it not only

limits eastward expansion of Asiatic species but also limits the westward expansion of North Pacific species. This filter bridge is further accentuated by Amchitka Pass [500 to 1000 m (275 to 550 fathoms) deep], which separates Amchitka Island from the Aleutian Islands to the east and which is a major point of exchange between the North Pacific Ocean and Bering Sea water masses (McAlister, 1971; McAlister and Favorite, Chap. 16, this volume).

The composition of Amchitka's fish fauna also reflects the island's distinctive littoral and near-shore topography. The extensive wide littoral benches and the broad sublittoral shelf on the North Pacific Ocean side of the island provide suitable habitat for large populations of littoral and inner sublittoral fishes.

HISTORICAL REVIEW

The first investigations of Aleutian fish fauna were made in 1741 by Georg Wilhelm Steller, a naturalist on the second Bering expedition. Steller, who accompanied Vitus Bering on the vessel *St. Peter*, discovered, named, and meticulously described a multitude of plants and animals, including 17 species of anadromous or marine fishes (Stejneger, 1936). Exploration and exploitation of

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the Aleutians by the Russian promyshlenniki, or fur hunters, followed soon thereafter. The original visit to Amchitka was probably either by the *Ieremiia* (Jeremiah) in 1753–1755 or by the *Petr i Pavel* (Sts. Peter and Paul) in 1756–1758. Both vessels were owned by Serebrennikov and captained by Bashmakov (Makarova, 1975). Although the promyshlenniki usually did not bother to collect “faunal specimens” other than sea mammal pelts, many Russian scientific expeditions carried naturalists who collected and described much of the newly encountered flora and fauna. Sarychef of the 1790–1792 Billings expedition, Tilesius and Langsdorff of the 1803–1806 Krusenstern expedition, Chamisso and Eschscholtz of the 1815–1818 Kotzebue expedition, Von Kittlitz, Postels, and Mertens of the 1826–1829 Lütke expedition, and Vosnesensky, on an expedition sponsored by the Leningrad Museum, all contributed significantly to the natural history of the Aleutians and Bering Sea. Ichthyofaunal specimens collected by Steller and succeeding Russian naturalists were formally described in the scientific literature by Tilesius, Pallas, Cuvier, Shmidt, and others (Jordan and Gilbert, 1899), the most comprehensive work being that of Pallas [*Zoographia Rosso-Asiatica* (1811–1842)] and Shmidt [*Pisces Marium Orientalium* (1904)].

Scientific investigations of Alaska and adjacent waters were instituted by the U. S. government soon after the purchase of Alaska from Russia in 1867 (see Fuller, Chap. 7, this volume, for a more complete discussion of scientific investigations in the western Aleutians after 1867). William H. Dall was in the first U. S. Coast and Geodetic Survey hydrographic and geographic reconnaissance of the Aleutians from 1871 to 1874, during which time he collected faunal specimens for deposit in the U. S. National Museum (Jochelson, 1925); he was the first American naturalist to study Amchitka's marine fishes (Dall, 1874 and 1877). From 1880 through the mid-1890s, the U. S. Coast Survey schooner *Yukon*, the U. S. Treasury revenue steamers *Corwin* and *Mohican*, and the U. S. Fish Commission steamer *Albatross* cruised the North Pacific Ocean and Bering Sea waters making hydrographic and meteorologic observations, patrolling for illicit fur seal hunters, and conducting biological collections. A. B. Alexander, Tarleton H. Bean, William H. Dall, Henry W. Elliott, Barton W. Evermann, Charles H. Gilbert, N. B. Miller, Charles H. Townsend, and L. M. Turner were among the notable collectors, naturalists, and ichthyologists accompanying these surveys; they also collected for the U. S. National Museum. Included in the records from this period

were two Amchitka Island collections, one by L. M. Turner in 1881 (Turner, 1886) and another by personnel from the steamer *Albatross*, June 6–7, 1906 (U. S. Bureau of Fisheries, 1907). Collection records, taxonomic descriptions, and synopses of findings (including Aleutian records and specimens from these early surveys deposited in the U. S. National Museum) were published by Bean (1882a; 1882b), Jordan and Gilbert (1883; 1899), Nelson (1887), Gilbert (1895), Tanner (1892–1896), Jordan and Starks (1904), and Evermann and Goldsborough (1907).

U. S. Fish and Wildlife Service expeditions to the Aleutians from 1936 to 1938 assessed birds and mammals and also studied marine fishes and invertebrates (Scheffer, 1959). These investigations documented 48 species of fishes indigenous to the archipelago and included descriptions by Schultz (1939) of a new genus and two new species.

The most comprehensive description of Aleutian ichthyofauna existing at the start of our work was that by Wilimovsky (1964); he described the distribution of 135 littoral fishes throughout the length of the Aleutian chain. Earlier, Wilimovsky (1954) had listed 222 marine fishes from “all waters south of the Bering Strait and north of the Alaska Peninsula, including the Aleutian chain, Pribilof Islands, St. Matthew Island, and St. Lawrence Island,” and had produced a provisional key to 241 species occurring within that range or more generally in the North Pacific Ocean (Wilimovsky, 1958). A survey of Amchitka's wildlife was also conducted by Fish and Wildlife Service biologists during the summer of 1962, in which they recorded 12 anadromous and marine species and several unidentified blennies, sculpins, liparids, and flounders (McCann, 1963).

Seventeen marine and anadromous fish species were observed in 1965 during the bioenvironmental safety program associated with the Long Shot nuclear test on Amchitka (Seymour and Nakatani, 1967).

Contemporary descriptive syntheses of North Pacific ichthyofauna, including some of the species encountered in these studies (Quast and Hall, 1972; Hart, 1973), have been used in the discussion in this chapter of the zoogeographical distribution of marine fishes that occur around Amchitka Island.

RECENT INVESTIGATIONS

The Fisheries Research Institute (FRI) of the University of Washington studied and evaluated the impact of two underground nuclear explosions

(Milrow on Oct. 2, 1969, and Cannikin on Nov. 6, 1971) on the marine fishes off Amchitka Island. The FRI fish investigations were conducted from the summer of 1967 to the fall of 1973 for the U. S. Atomic Energy Commission (AEC) by sub-contract with the Columbus Laboratories of Battelle Memorial Institute (BCL). Reports of investigations were submitted annually to BCL and are summarized in Nakatani and Burgner (1974). Although previous information on marine fishes off Amchitka Island was largely limited to compilation of species check lists, FRI fish sampling also determined the distribution, relative abundance, and life-history aspects of fish species found in the vicinity of the test sites. The sampling was concentrated in summer and fall to coincide with the planned fall detonation times and because the frequent inclement weather limited sampling during winter and spring.

This chapter summarizes the basic information gathered on marine fishes off Amchitka Island and the extent to which their populations were affected by the underground tests. Figure 1 shows the location of coastal features of Amchitka.

MATERIALS AND METHODS

Fishing Vessels

In 1967 and 1969 the *M. V. Paragon*, a 27-m (90-ft) trawler, was used in the deeper offshore waters [depths greater than 38 m (125 ft)], and a variety of small outboard boats were used in the nearshore waters. From 1970 to 1972 the *M. V. Commander*, a 26-m (85-ft) purse seiner with multiple-gear capabilities, was used principally during fall months. Larger inboard-outboard boats were available during the latter period, which permitted nearshore sampling at greater distances from boat-launching sites.

The offshore sampling from the research vessels included bottom and midwater trawling, purse seining, salmon gill-netting and long-lining, bottom dredging, and the fishing of crab traps. Nearshore sampling included the use of bottom and surface experimental gill nets and trammel nets, bottom and surface longlines, shrimp, crab, minnow, and amphipod traps, plankton nets, rotenone, and miscellaneous hook-and-line and hand collections.

Gear Types

Bottom Trawl. The bottom trawl, the primary offshore sampling gear, was a 400-mesh two-seam eastern bottom (otter) trawl with a 22-m (71-ft) headrope and a 29-m (95-ft) footrope constructed

with a 10-cm (4-in.)* mesh cod end of 96-thread nylon. Chafing mats protected the bottom and cod end, and rollers of various sizes were used on the footrope, depending on suspected bottom roughness. The net was fished with Formosan-type otter boards that weighed 430 kg (950 lb) in 1967 and 340 kg (750 lb) in 1969 and later years.

Midwater Trawl. The midwater trawl was a 27-m (90-ft)-long modified herring trawl with a 6-m (20-ft)-square opening which was fished with 227-kg (500-lb) otter boards at approximately 4 knots. Webbing ranged from 7.5-cm (3-in.) wings to 1.25-cm (0.5-in.) cod end. A standard 3-m (10-ft) Isaacs-Kidd midwater net was also used to capture smaller fishes missed by the larger midwater trawl.

Purse Seine. The purse seine was approximately 730 m (2400 ft) long and 37 m (120 ft) deep and was hung with 5-cm (2-in.)-mesh, 15-18 thread, knotless nylon web except for the center bunt, which was of 2.5-cm (1-in.) mesh. The net was generally held open toward the current to the northwest for 1.5 to 2 hr. The purse seine was fished only briefly in 1970.

Salmon Gill Nets. The surface salmon gill nets were composed of six to ten 91-m (300-ft)-long by 5.5-m (18-ft)-deep shackles of multifilament nylon that ranged in mesh size from 6.4 to 11.4 cm (2.5 to 4.5 in.).

Bottom Gill Nets. Monofilament gill nets were 2.7 m (9 ft) deep with six 12-m (40-ft, hung measure) panels of 2.5-, 3.8-, 5.0-, 6.4-, 7.6-, and 10-cm (1-, 1.5-, 2-, 2.5-, 3-, and 4-in.) web and with a low-buoyancy float line, which allowed the net to sink to the bottom.

Surface Gill Nets. Monofilament surface gill nets were identical to the sinking gill net except that they contained more floats.

Trammel Nets. The trammel nets used were made of green-dyed nylon outer walls of 50-cm (20-in.) web and inner walls of 10-cm (4-in.) web and were 91 m (300 ft) long and 1.8 m (6 ft) deep. They were weighted to sink but were buoyed sufficiently to hold them vertically above the bottom.

Salmon Longlines. Japanese surface salmon longlines were used to catch salmon offshore during the 1967 through 1969 sampling period. This gear generally consisted of 10 skates, each with a 22.6-kg test vinylon main line that was

*All mesh sizes are stretched measure.

Fig. 1—Location of coastal features of Amchitka Island, Alaska.

approximately 138 m (450 ft) long with 49 evenly spaced [2.3 m (7.5 ft)] size-8 hooks on 1-m(3-ft)-long 10-kg (22-lb) test monofilament leaders. Ten evenly spaced wooden floats buoyed each skate. The bait used was 7- to 10-cm(3- to 4-in.)-long dried salted anchovy (*Engraulis japonica*). The total length of the longline set was approximately 1.4 km (0.75 nautical mile).

Surface Longlines. Surface longlines fished nearshore were made from standard 49-hook Japanese salmon longline gear with floats spaced five hooks apart. Octopus was most often used as bait.

Bottom Longlines. Longlines consisting of the standard 49-hook Japanese salmon longline without floats or a heavy-duty 8- to 10-hook anchored halibut longline were fished on the bottom in nearshore waters. Squid or octopus was usually used as bait.

Anchor Dredge. An anchor dredge with an 89-by 38-cm (35-by 15-in.) opening from the inclined plate into the 10-cm (4-in.) nylon 96-mesh collecting bag was cast from the offshore vessel and retrieved after digging into the bottom or briefly towed along the bottom surface. Several fish were caught with the benthos brought up with this dredge.

Shrimp Traps. Experimental shrimp traps [45 by 45 by 75 cm (18 by 18 by 30 in.)] were used in water 3 to 60 m (10 to 200 ft) deep. Fishes caught nearshore were used as bait. Several species of fish, which were probably attracted to the amphipods that were feeding on the bait, were captured in the traps.

Crab Traps. Commercial king crab pots [1.8 m (or 6 ft) in diameter] were used in 1967 but in later years were replaced by 86-cm(34-in.)-diameter Taylor crab traps. Nearshore fishes were used as bait. Fishes and various invertebrates as well as crab were captured in these pots.

Minnow Traps. Commercially built polypropylene traps, 43 cm (17 in.) long by 23 cm (9 in.) in diameter with 2.5-cm (1-in.) openings in each end, were baited with nearshore fish and usually anchored in littoral pools.

Amphipod Traps. Prior to the initiation of plankton pump sampling, amphipod traps made from 3.7-liter (1-gal) wide-mouth nalgene bottles with an inverted cone opening were used to collect scavenging crustaceans. Bait included octopus and nearshore fishes. A few small fishes were captured along with the invertebrates.

Plankton Nets. Plankton nets were used to collect fish eggs and larvae in nearshore areas. The

nets were of standard 0.5-m (2-ft) No. 3 mesh (0.324-mm aperture) with a flowmeter attached. Both vertical and horizontal tows were made.

Rotenone. This poison was applied in 500-g warmwater-paste batches to isolated tide pools where suitable concentrations could be maintained and confined; larger tide pools required two batches. Tide pools selected ranged from less than 2.8 m³ (100 ft³) to over 5.7 m³ (200 ft³) in volume, differed in algal cover and substrate, and yielded a wide diversity of species.

Miscellaneous: Hook-and-Line and Hand Collections. These sampling methods were productive but were considered incidental and more selective than other sampling procedures. Hand collections included fishes captured during scuba surveys with a "slurp gun" or by hand during invertebrate and algae collections in the littoral zone.

Sampling Schedules and Areas

Sampling schedules varied with the type of gear used. Offshore bottom trawling and purse seining were usually done during the day and midwater trawling at night. An echo sounder was used during bottom trawling to detect the presence of fishes, to select the fishing depth and suitable bottom types for nearshore set net fishing, and to locate fishes during midwater trawling and purse seining. Surface salmon gill nets were fished at night, and surface salmon longlines were usually fished for a 1- to 3-hr period before daybreak.

Night sampling in small boats was not considered safe. Therefore most nearshore sampling took place during the day when weather allowed. Nets and longlines were commonly fished overnight except during winter and spring sampling when the unpredictable weather conditions limited sets to 2 to 5 hr during daylight. Thus fishing time per set varied from 2 to 24 hr, depending on safety considerations, the gear type, and season. Owing to the destructive predation of captured fishes by amphipods, bottom-set nets could not be fished for more than a couple of hours when stomachs or other critical samples were to be retained.

Constraints on the sampling program included the selectivity of the fishing gear; inability to sample at all seasons, particularly offshore where an expensive chartered vessel was necessary; and selection of sampling sites near underground nuclear test sites, which concentrated nearly all marine fish sampling effort around the southeast part of Amchitka Island. These limits should be considered in the following discussion of Amchitka's marine fishes and in the interpretation of results.

Sample Processing. All catches were counted (or total weight estimated for large trawl hauls) and recorded by species along with such information as date, depth, location, time of set, and time of recovery. Tow and wind directions were also recorded for all trawl catches.

During the first few years of the program, all fishes captured in nearshore waters were retained for life-history, meristic, and food-web studies. In later years some species were retained for continuing food-web studies whereas the rest were counted and released alive.

All the fishes returned to the field laboratory at Amchitka were measured for total length to the nearest millimeter and weighed to the nearest gram. Some species of particular interest were preserved whole in 10% buffered Formalin or frozen and returned to the Seattle laboratory as museum specimens or for further examination. However, most fishes were processed in the Amchitka laboratory for such information as sex, gonad weight, age (otolith or scale), and stomach sample. All fishes and accompanying information were identified by code numbers and sampling set numbers. Data were transferred to computer cards for ease of analysis. Several thousand fishes were processed each year.

Three basic taxonomic keys to fishes of the North Pacific—Andriyashev (1954), Clemens and Wilby (1961), and Wilimovsky (1958)—were used to identify the fishes collected at Amchitka. Further verifications were made from more specific taxonomic keys in the ichthyological literature.

Food-Web Studies. The description of the Amchitka marine food web resulted from the quantitative analysis of the stomach contents from almost 2000 fish specimens obtained during the Amchitka collections. The wet weight, number, and taxa of prey organisms and rank evaluations of stomach fullness and digestion were determined for each stomach sample (Burgner et al., 1969; Simenstad, 1971a). The raw data were analyzed specifically for the percentage of total weight of stomach contents by food organism with frequency of occurrence and numerical abundance providing supporting indexes of feeding habits. The ensemble of stomach sample data was analyzed with digital-computer programs designed specifically to address the Amchitka data set.

Tagging Studies. Prompted by the great abundance of rock greenling (*Hexagrammos lagocephalus*) in nearshore waters, in 1968 through 1971 we undertook to study their growth and movements by tagging. Rock greenling captured in the sampling nets were measured, weighed, sexed,

tagged with green "spaghetti" tags measuring 3.8 cm (1.5 in.) long, and then released in the general area of capture. Posters requesting the return of tagged rock greenling from sport fishermen at Amchitka Island were displayed.

RESULTS AND DISCUSSION

Fish Occurrence

Table 1 lists the 92 identifiable species documented from Amchitka's nearshore and adjacent offshore marine waters. In addition, three species of cottids were identified from ichthyoplankton but do not necessarily represent established populations at Amchitka.

Contemporary accounts of North Pacific fish fauna [Quast and Hall (1972) and Hart (1973)] were used to group the species caught at Amchitka according to their geographical distributions (Table 2). According to these sources, nine of the species were known to range throughout the temperate and torrid zones of the North Pacific—mostly epipelagic, mesopelagic, and bathypelagic fishes ranging from near the surface to 3000 m (1650 fm) and deeper. Of the Amchitka species, 32 have been recorded as occurring throughout the temperate* and subarctic waters of the North Pacific basin (amphi-Pacific) and 21 are confined to the subarctic water masses of the North Pacific Ocean and Bering Sea. Twenty-four species have previously been reported in the eastern portion of the temperate and subarctic North Pacific only; of these, *Raja trachura*, *Coryphaenoides filifera*, and *Radulinus asprellus* had not been reported in the Aleutians before the FRI Amchitka studies, and *Chirolophis nugator*, *Sebastes babcocki*, and *Glyptocephalus zachirus* had not been recorded west of Unalaska Island in the easternmost region of the archipelago. Three species are considered to occur universally in arctic and subarctic northern hemisphere waters, one in north temperate waters. The longnose lancetfish (*Alepisaurus ferox*) is known throughout the tropic to subarctic regions of both the Atlantic and Pacific Oceans and the Mediterranean Sea. The toothed cod (*Arctogadus borisovi*), previously known from the arctic seas of North America only, was also captured during our bottom trawling at Amchitka, a significant southern extension of its documented range.

Three additional cottid species, *Furcina ishikawae*, *Ocynectes maschaus*, and *Scorpaenichthys marmoratus* (the cabezon), were iden-

*Temperate waters are here defined as extending to 45°N latitude.

Table 1—Marine Fishes Collected at Amchitka, 1967 Through 1972*

Scientific name	Common name
Class Cyclostomi	
Order Petromyzontiformes	
Family Petromyzonidae	Lampreys
<i>Entosphenus tridentatus</i> (Gairdner in Richardson, 1836)	Pacific lamprey
Class Chondrichthyes	
Order Squaliformes	
Family Lamnidae	Mackerel sharks
<i>Lamna ditropis</i> (Hubbs and Follett, 1947)	Salmon shark
Order Rajiformes	
Family Rajidae	Skates
<i>Raja binoculata</i> (Girard, 1854)	Big skate
<i>Raja parmifera</i> (Bean, 1881)	Alaska skate
<i>Raja trachura</i> (Gilbert, 1891)	Roughtail skate
Class Osteichthyes	
Order Salmoniformes	
Family Salmonidae	Salmon and trout
<i>Oncorhynchus gorbuscha</i> (Walbaum, 1792)	Pink salmon
<i>Oncorhynchus keta</i> (Walbaum, 1792)	Chum salmon
<i>Oncorhynchus kisutch</i> (Walbaum, 1792)	Coho salmon
<i>Oncorhynchus nerka</i> (Walbaum, 1792)	Sockeye salmon
<i>Oncorhynchus tshawytscha</i> (Walbaum, 1792)	Chinook salmon
<i>Salvelinus malma</i> (Walbaum, 1792)	Dolly Varden
Family Bathylagidae	Deepsea smelts
<i>Bathylagus milleri</i> † (Jordan and Gilbert, 1898)	Stout blacksmelt
<i>Bathylagus stibius</i> (Gilbert, 1890)	California smoothtongue
Family Gonostomatidae	Lightfishes
<i>Cyclothone microdon</i> † (Gunther, 1878)	Veiled anglemouth
Family Chauliodontidae	Viperfishes
<i>Chauliodus macouni</i> (Bean, 1890)	Pacific viperfish
Order Myctophiformes	
Family Alepisauridae	Lancetfishes
<i>Alepisaurus ferox</i> (Lowe, 1833)	Longnose lancetfish
Family Myctophidae	Lanternfishes
<i>Diaphus theta</i> (Eigenmann and Eigenmann, 1890)	California headlightfish
<i>Electrona arctica</i> † (Lutken, 1892)	Bigeye lanternfish
<i>Lampanyctus regalis</i> (Gilbert, 1892)	Pinpoint lampfish
<i>Stenobrachius leucopsarus</i> (Eigenmann and Eigenmann, 1890)	Northern lampfish
<i>Tarletonbeania crenularis</i> (Jordan and Gilbert, 1880)	Blue lanternfish
Order Gadiformes	
Family Gadidae	Codfishes
<i>Arctogadus borisovi</i> (Drjagin, 1932)	Toothed cod
<i>Gadus macrocephalus</i> (Tilesius, 1810)	Pacific cod
<i>Theragra chalcogramma</i> (Pallas, 1811)	Walleye pollock
Family Macrouridae	Grenadiers
<i>Coryphaenoides acrolepis</i> † (Bean, 1883)	Roughscale rattail
<i>Coryphaenoides filifera</i> † (Gilbert, 1895)	Filamented rattail
Order Gasterosteiformes	
Family Gasterosteidae	Sticklebacks
<i>Gasterosteus aculeatus</i> (Linnaeus, 1758)	Threespine stickleback
Order Perciformes	
Family Trichodontidae	Sandfishes
<i>Trichodon trichodon</i> (Tilesius, 1811)	Pacific sandfish
Family Bathymasteridae	Ronquils
<i>Bathymaster caeruleofasciatus</i> (Gilbert and Burke, 1912)	Alaskan ronquil
<i>Bathymaster signatus</i> (Cope, 1873)	Searcher
<i>Ronquilus jordani</i> (Gilbert, 1888)	Northern ronquil
Family Stichaeidae	Pricklebacks
<i>Alectrias alectrolophus</i> (Pallas, 1811)	Stone cockscomb
<i>Anoplarchus purpureus</i> (Gill, 1861)	High cockscomb
<i>Chirolophis nugator</i> (Jordan and Williams, 1895)	Mosshead warbonnet
<i>Gymnoclinus cristulatus</i> (Gilbert and Burke, 1912)	Trident pricklyback

(Table continues on page 458.)

Table 1 (Continued)

Scientific name	Common name
<i>Phytichthys chirus</i> (Jordan and Gilbert, 1880)	Ribbon prickleback
<i>Poroclinus rothrocki</i> (Bean, 1890)	Whitebarred prickleback
Family Pholidae	Gunnels
<i>Pholis dolichogaster</i> (Pallas, 1811)	Stippled gunnel
<i>Pholis laeta</i> (Cope, 1873)	Crescent gunnel
Family Ptilichthyidae	Quillfishes
<i>Ptilichthys goodei</i> (Bean, 1881)	Quillfish
Family Zaproridae	Prowfishes
<i>Zaprora silenus</i> (Jordan, 1896)	Prowfish
Family Ammodytidae	Sand lances
<i>Ammodytes hexapterus</i> (Pallas, 1811)	Pacific sand lance
Family Scorpaenidae	Scorpionfishes
<i>Sebastes aleutianus</i> (Jordan and Evermann, 1898)	Rougheye rockfish
<i>Sebastes alutus</i> (Gilbert, 1890)	Pacific ocean perch
<i>Sebastes babcocki</i> (Thompson, 1915)	Redbanded rockfish
<i>Sebastes ciliatus</i> (Tilesius, 1810)	Dusky rockfish
<i>Sebastes polyspinis</i> (Tarantetz and Moiseev, 1933)	Northern rockfish
<i>Sebastes proriger</i> (Jordan and Gilbert, 1880)	Redstripe rockfish
<i>Sebastolobus alascanus</i> (Bean, 1890)	Shortspine thornyhead
Family Anoplopomatidae	Sablefishes
<i>Anoplopoma fimbria</i> (Pallas, 1811)	Sablefish
Family Hexagrammidae	Greenling
<i>Hexagrammos decagrammus</i> (Pallas, 1810)	Kelp greenling
<i>Hexagrammos lagocephalus</i> (Pallas, 1810)	Rock greenling
<i>Pleurogrammus monopterygius</i> (Pallas, 1810)	Atka mackerel
Family Cottidae	Sculpins
<i>Blepsias cirrhosus</i> (Pallas, 1811)	Silverspotted sculpin
<i>Clinocottus acuticeps</i> (Gilbert, 1895)	Sharpnose sculpin
<i>Clinocottus embryum</i> (Jordan and Starks, 1895)	Calico sculpin
<i>Enophrys diceratus</i> (Pallas, 1787)	Antlered sculpin
<i>Gymnocanthus galeatus</i> (Bean, 1881)	Armorhead sculpin
<i>Gymnocanthus pistilliger</i> § (Pallas, 1811)	Threaded sculpin
<i>Hemilepidotus hemilepidotus</i> (Tilesius, 1810)	Red Irish lord
<i>Hemilepidotus jordani</i> (Bean, 1881)	Yellow Irish lord
<i>Hemitripterus bolini</i> (Myers, 1934)	Bigmouth sculpin
<i>Icelus canaliculatus</i> § (Gilbert, 1895)	
<i>Malacocottus kincaidii</i> (Gilbert and Thompson, 1905)	Blackfin sculpin
<i>Myoxocephalus polyacanthocephalus</i> (Pallas, 1811)	Great sculpin
<i>Nautichthys pribilovius</i> (Jordan and Gilbert, 1899)	Eyeshade sculpin
<i>Radulinus asprellus</i> (Gilbert, 1890)	Slim sculpin
<i>Triglops forficata</i> (Gilbert, 1895?)	Scissortail sculpin
<i>Triglops metopias</i> § (Gilbert and Burke, 1912)	
<i>Triglops pingeli</i> (Reinhardt, 1832)	Ribbed sculpin
<i>Triglops scepticus</i> (Gilbert, 1895)	Spectacled sculpin
Family Agonidae	Poachers
<i>Agonus acipenserinus</i> (Tilesius, 1811)	Sturgeon poacher
<i>Aspidophoroides bartoni</i> (Gilbert, 1895)	Aleutian alligatorfish
<i>Hypsogonus quadricornis</i> (Cuvier, 1829)	Fourhorn poacher
<i>Pallasina barbata</i> (Steindachner, 1876)	Tubenose poacher
<i>Sarritor leptorhynchus</i> (Gilbert, 1895)	Longnose poacher
Family Cyclopteridae	Lumpfishes and snailfishes
<i>Aptocyclus ventricosus</i> (Pallas, 1770)	Smooth lump sucker
<i>Careproctus gilberti</i> † (Burke, 1912)	Small disk snailfish
<i>Careproctus phasma</i> § (Gilbert, 1895)	
<i>Crystallichthys cyclospilus</i> (Gilbert and Burke, 1912)	Blotched snailfish
<i>Eumicrotremus orbis</i> (Gunther, 1861)	Pacific spiny lump sucker
<i>Lethotremus muticus</i> § (Gilbert, 1893)	
<i>Liparis callyodon</i> (Pallas, 1811)	Spotted snailfish
<i>Liparis megacephalus</i> § (Burke, 1912)	
<i>Nectoliparis pelagicus</i> (Gilbert and Burke, 1912)	Tadpole snailfish
<i>Polypera greeni</i> (Jordan and Starks, 1895)	Lobefin snailfish

Table 1 (Continued)

Scientific name	Common name
Order Pleuronectiformes	
Family Pleuronectidae	Righteye flounders
<i>Atheresthes stomias</i> (Jordan and Gilbert, 1880)	Arrowtooth flounder
<i>Glyptocephalus zachirus</i> (Lockington, 1879)	Rex sole
<i>Hippoglossoides elassodon</i> (Jordan and Gilbert, 1880)	Flathead sole
<i>Hippoglossus stenolepis</i> (Schmidt, 1904)	Pacific halibut
<i>Lepidopsetta bilineata</i> (Ayres, 1855)	Rock sole
<i>Reinhardtius hippoglossoides</i> (Walbaum, 1792)	Greenland halibut
Ichthyoplankton specimens; not captured as adults:	
Order Perciformes	
Family Cottidae	
<i>Furcina ishikawae</i> (Jordan and Starks, 1904)¶	
<i>Ocynectes maschaus</i> (Jordan and Starks, 1904)¶	
<i>Scorpaenichthys marmoratus</i> (Ayers, 1854)	

*Nomenclature and species arrangement from the American Fisheries Society (1970) and Greenwood et al. (1966) except

†Hart (1973).

‡Renamed from *P. thompsoni* (Chapman, 1944), Hart (1973).

§Quast and Hall (1972).

¶Jordan and Starks (1904).

tified* from Amchitka ichthyoplankton. *Furcina ishikawae* and *Ocynectes maschaus* represent species hitherto believed to be restricted to the western North Pacific basin and unreported in North America, including the Aleutians. *Scorpaenichthys marmoratus* is a temperate eastern North Pacific species not previously reported west of the Gulf of Alaska. Although the identification of the larvae of the two Japanese species is reasonably positive, the larval cabezon could be confused with some species of the genus *Myoxocephalus*. In view of the lack of adult forms in the collections, the existence of viable reproducing populations of these particular cottids in the Amchitka vicinity is doubtful. In a true ecological sense, then, they are not confirmed as components of the Amchitka fish fauna.

We note that, although 24 species of fishes at Amchitka are represented as being near the western limit of their Alaskan distribution (including six westward extensions of known range), none of the species collected as adults at Amchitka are exclusively Asiatic species near the eastern limit of their distribution. The distinctive position of Amchitka Island amidst the North Pacific current systems, pointed out by Wilimovsky (1964) and discussed earlier herein, appears to be an important factor

influencing the composition of Amchitka's fish fauna. The occurrence of two exclusively Asiatic cottids in our ichthyoplankton samples indicates, however, limited immigration from faunal sources to the west. Why these species have not become established remains a matter for speculation. Possibilities include competition from already established species, environmental conditions preventing maturation of larvae or juveniles, and predation.

The distribution of Amchitka's marine fishes according to the depth from which we collected them is shown in Fig. 2. Complete depth ranges are indicated by thin lines, depths of relatively high abundance by the heavy portion of these lines, and the location of infrequent captures by circles. Sampling methods produce biases in these patterns; so they must be considered as only approximate. (Fishes may occur at depths unsampled, fishes may change to other depths at other seasons, and some gears sample incompletely or sample during ascent from or descent to the desired depth.)

Amchitka Fish Communities

Following Whittaker (1970), we define a biotic community as a natural assemblage of populations that live together in a distinguishable habitat and interact with each other, "forming together a distinctive living system with its own composition, structure, environmental relations, development, and function." In earlier reports we discussed Amchitka fish communities subjectively on the basis of the species distribution according to four

*Taxonomic determination of ichthyoplankton specimens was made by W. E. Barraclough, Fisheries Research Board of Canada, Nanaimo Biological Station, Nanaimo, B.C., Canada.

Table 2—Zoogeographic Distributions of Marine Fishes Collected at Amchitka Island, Alaska, 1967 Through 1973 *

Distribution	Species	Distribution	Species
Temperate and sub-arctic North Pacific Ocean; Japan to western North America (amphi-Pacific) (32 species)	<i>Oncorhynchus gorbusha</i> <i>O. keta</i> <i>O. kisutch</i> <i>O. nerka</i> <i>O. tshawytscha</i> <i>Salvelinus malma</i> <i>Chauliodus macouni</i> <i>Gadus macrocephalus</i> <i>Theragra chalcogramma</i> <i>Trichodon trichodon</i> <i>Bathymaster signatus</i> <i>Ptilichthys goodei</i> <i>Zaprora silenus</i> <i>Sebastes alutus</i> <i>Sebastolobus alascanus</i> <i>Anoplopoma fimbria</i> <i>Hexagrammos lagocephalus</i> <i>Pleurogrammus monopterygius</i> <i>Blepias cirrhosus</i> <i>Malacocottus kincaidi</i> <i>Myoxocephalus polyacanthocephalus</i> <i>Hypsagonus quadricornis</i> <i>Pallasina barbata</i> <i>Aptocyclus ventriosus</i> <i>Careproctus gilberti</i> <i>Eumicrotremus orbis</i> <i>Nectoliparis pelagicus</i> <i>Atheresthes stomias</i> <i>Hippoglossoides elassodon</i> <i>Hippoglossus stenolepis</i> <i>Lamna ditropis</i> <i>Lepidopsetta bilineata</i>	Eastern portion of the temperate and subarctic North Pacific, including the Aleutian Islands (24 species)	<i>Careproctus phasma</i> <i>Crystallichthys cyclospilus</i> <i>Raja trachura</i> † <i>Coryphaenoides filifera</i> ‡ <i>Chirolophis nugator</i> § <i>Ronquilus jordani</i> <i>Raja binoculata</i> <i>Anoplarchus purpureus</i> <i>Gymnocrinus cristulatus</i> <i>Phytichthys chirus</i> <i>Poroclinus rothrocki</i> <i>Pholis laeta</i> <i>Sebastes aleutianus</i> <i>S. babcocki</i> § <i>S. ciliatus</i> <i>S. proriger</i> <i>Hexagrammos decagrammus</i> <i>Clinocottus acuticeps</i> <i>C. embryum</i> <i>Radulinus asprellus</i> ‡ <i>Triglops metopias</i> <i>Lethotremus muticus</i> <i>Liparis callyodon</i> <i>L. megacephalus</i> <i>Polypera greeni</i> <i>Glyptocephalus zachirus</i> §
Subarctic North Pacific Ocean and Bering Sea (21 species)	<i>Entosphenus tridentatus</i> <i>Raja parmifera</i> <i>Bathymaster caeruleofasciatus</i> <i>Alectrias alectrolophus</i> <i>Pholis dolichogaster</i> <i>Sebastes polyspinis</i> <i>Enophrys dicerus</i> <i>Gymnancistrus galeatus</i> <i>G. pistilliger</i> <i>Hemilepidotus hemilepidotus</i> <i>H. jordani</i> <i>Hemitripterus bolini</i> <i>Icelus canaliculatus</i> <i>Nautichthys pribilovius</i> <i>Triglops forficatus</i> <i>T. scepticus</i> <i>Agonus acipenserinus</i> <i>Aspidophoroides bartoni</i> <i>Sarritor leptorhynchus</i>	Torrid and temperate North Pacific (9 species)	<i>Bathylagus milleri</i> <i>B. stilbius</i> <i>Cyclothone microdon</i> <i>Diaphus theta</i> <i>Electrona arctica</i> <i>Lampanyctus regalis</i> <i>Stenobrachius leucopsarus</i> <i>Tarletonbeani crenularis</i> <i>Coryphaenoides acrolepis</i> <i>Ammodytes hexapterus</i> <i>Triglops pingeli</i> <i>Reinhardtius hippoglossoides</i>
		Universal in the North Pacific Basin, Bering Sea, and Arctic Ocean	<i>Gasterosteus aculeatus</i>
		Universal in the north temperate oceans	<i>Arctogadus borisovi</i> §
		Arctic seas of North America	<i>Alepisaurus ferox</i>
		Tropical to sub-arctic regions of the Atlantic and Pacific Oceans	

*This list does not include three unrecorded ichthyoplankton species as discussed in the text.

†Extension of known range: previously unrecorded west of the Gulf of Alaska.

‡Extension of known range: previously unrecorded west of Unalaska Island.

§Extension of known range: newly recorded in the subarctic North Pacific Ocean.

distinct habitats (Isakson, Simenstad, and Burgner, 1971). Quantitative association analyses of the Amchitka collection data with the use of recurrent group analysis (Fager, 1957) has identified 13 distinct groups and associated species with an affinity index of at least 0.40 (Fig. 3). These groupings define the structure of four offshore communities and one inshore community, a littoral assemblage. Many species, especially those captured in the inner sublittoral and neritic waters around Amchitka, did not fall into significant assemblages when an affinity index of 0.40 was used as a test of significance. When these results are incorporated with a detailed examination of species distributions, the existence of seven identifiable fish communities, identified here by their characteristic habitats, is suggested: Epipelagic, mesopelagic, offshore demersal/rock-sponge, offshore demersal/sand-gravel, inshore/sand-gravel,* inshore/rock-algae,* and littoral (Fig. 4 and Table 3), with some variations in species associations detectable within several of these. The community descriptions that follow are basically assembled with the use of these qualitative characterizations; more subtle relationships, such as heterogeneity within a habitat, mechanisms of species associations, and microhabitats, cannot be identified from the limited scope of our data.

Epipelagic Community. Fishes comprising the epipelagic community occur in the oceanic waters off Amchitka between the surface and 200 m. This community was sampled by salmon longline, surface-gill-net, and purse-seine fishing in the upper 10 m of these waters; the midwater trawl sampled the deeper portion of the habitat.

This community was characterized by a relatively low diversity of fishes, only 11 species having been found in it. The fishes are highly mobile, often representing migratory species, such as five of the six species of Pacific salmon (*Oncorhynchus* spp.). Only one two-species group, which was composed of *Oncorhynchus keta*, the chum salmon, and *O. nerka*, the sockeye salmon, was defined for this habitat by the recurrent group analysis. The majority of the salmonids found in the epipelagic community were chum and sockeye salmon. Other FRI studies have indicated that most of the chum salmon in the Amchitka area are of Asian origin and that the majority of the sockeye salmon are from Bristol Bay, Alaska, watersheds (Hartt, 1966; Nakatani and Burgner, 1974). The sockeye caught at

Amchitka were preponderantly 3-year-old fish (having spent 2 years in freshwater and 1 year in the ocean) with a scattering of 4 year olds (2 years in freshwater and 2 years in the ocean). Both sockeye and chum are immature fishes moving in a general westerly drift exploiting the feeding grounds of the Bering Sea and the North Pacific Ocean immediately south of the west-central Aleutians. The only hexagrammid truly pelagic as an adult, the Atka mackerel, was also an abundant member of the epipelagic community. The Atka mackerel traveled in dense schools, especially when entering the inshore waters of the islands during June and July for spawning. The rock greenling, the adult dominant of the inshore/rock-algae community, was also found in epipelagic schools of 1- to 3-year-old juveniles. Pacific sand lance were frequently observed in extensive rapidly swimming schools near the surface at night.

Mesopelagic Community. A distinct community of fishes apparently exists between 200 and 1000 m in the oceanic mesopelagic zone. We sampled only the upper region of this zone (200 to 300 m; 324 m maximum depth) and only during nighttime midwater trawling, concentrating in the productive upwelling waters of the Bering Sea off the eastern end of the island. Only slightly more diverse (18 species versus 11) than the epipelagic community, the mesopelagic community is dominated by lanternfish (family Myctophidae), deepsea smelt (family Bathylagidae), lightfish (family Gonostomatidae), and viperfish (family Chauliodontidae). All are typically zooplankton-feeding fishes and with their predators, grenadiers (family Macrouridae) and longnose lancetfish (family Alepisauridae), apparently perform extensive nightly vertical migrations for feeding in the upper mesopelagic layers.

We optimized our midwater trawl catches in sampling this community by using echo-sounding equipment to find the depth of the deep-water plankton and the associated fishes (deep-scattering layer). In the rich upwelling area, maximum catches exceeded 300 fish per hour compared to 10 fish per hour in other areas sampled. Peak abundance and species diversity in the samples occurred between 2400 and 0400 (BDT). In the most productive trawl sets, northern lampfish, California headlightfish, bigeye lanternfish, and Pacific viperfish were the most abundant fishes.

Catches of fishes corresponded closely with catches of euphausiids, mysids, and carid shrimp, common prey organisms of these fishes.

The recurrent group analysis suggested a microstructure to this community and definite associations between some midwater fishes and associated

*No significant recurrent groups were found in these communities at the affinity index selected as a test of significance.

Fig. 3—Species associations of marine fishes and some associated invertebrates (dashed lines), Amchitka Island, 1967 to 1973, according to Fager's (1957) recurrent group analysis (affinity index, 0.40; sample size, 468).

Fig. 4—Diagrammatic sketch showing marine habitats associated with Amchitka fish communities. (The 200-m depth division in the pelagic zone does not apply to the demersal habitats or communities.)

Table 3—Relative Distribution of Amchitka Marine Fishes According to Seven Identifiable Communities Identified by Their Characteristic Habitats

	Epipelagic	Mesopelagic	Offshore demersal/ rock— sponge	Offshore demersal/ sand— gravel	Inshore/ sand— gravel	Inshore/ rock— algae	Intertidal
<i>Lamna ditropis</i>	*						
<i>Oncorhynchus gorboscha</i>	†				†		
<i>O. keta</i>	†						
<i>O. kisutch</i>	†				†		§
<i>O. nerka</i>	†						
<i>O. tshawytscha</i>	†						
<i>Alepisaurus ferox</i>	†	†					
<i>Ammodytes hexapterus</i>	¶			†	†		
<i>Pleurogrammus monopterygius</i>	†				†		
<i>Entosphenus tridentatus</i>		*					
<i>Bathylagus milleri</i>							
<i>B. stilbius</i>		¶					
<i>Cyclothone microdon</i>		†					
<i>Chauliodus macouni</i>		¶					
<i>Diaphus theta</i>		¶					
<i>Electrona arctica</i>		¶					
<i>Lampanyctus regalis</i>		†					
<i>Stenobrachius leucopsarus</i>		¶					
<i>Tarletonbeani crenularis</i>		*					
<i>Arctogadus borisovi</i>				*			
<i>Coryphaenoides acrolepis</i>		†					
<i>C. filifera</i>		*					
<i>Ptilichthys goodei</i>		*					
<i>Zaprora silenus</i>		*					
<i>Nectoliparis pelagicus</i>		¶					
<i>Eumicrotremus orbis</i>		†	†				
<i>Raja binoculata</i>				*			
<i>R. parvifera</i>			*				
<i>R. trachura</i>			†				
<i>Gadus macrocephalus</i>			¶	†	†	†	
<i>Theragra chalcogramma</i>		†	¶		†		
<i>Ronquillus jordani</i>			†				
<i>Alectrias alectrolophus</i>			*				
<i>Gymnoclinus cristulatus</i>			*				
<i>Poroclinus rothrocki</i>			*				
<i>Sebastes aleutianus</i>			*				
<i>S. alutus</i>			¶				
<i>S. babcocki</i>			*				
<i>S. polyspinis</i>			†				
<i>S. proriger</i>			†				
<i>Sebastolobus alascanus</i>			*				
<i>Anoplopoma fimbria</i>			*				
<i>Enophrys dicerca</i>			*				
<i>Hemilepidotus jordani</i>			†	†			
<i>Hemitripterus bolini</i>			*	*			
<i>Icelus canaliculatus</i>			*	*			
<i>Malacocottus kincaidii</i>			¶				
<i>Myoxocephalus polyacanthocephalus</i>			†			†	§
<i>Triglops forficata</i>			†		†		
<i>T. metopias</i>			†				

(Table continues on page 466.)

Table 3—(Continued)

	Epipelagic	Mesopelagic	Offshore demersal/ rock— sponge	Offshore demersal/ sand— gravel	Inshore/ sand— gravel	Inshore/ rock— algae	Intertidal
<i>T. scepticus</i>			†	†			
<i>Careproctus gilberti</i>			*				
<i>C. phasma</i>			*				
<i>Lethotremus muticus</i>			*				
<i>Liparis megacephalus</i>			*				
<i>Gymnocanthus galeatus</i>				†	¶		
<i>Hypsagonus quadricornis</i>				*			
<i>Sarritor leptorhynchus</i>				*			
<i>Atheresthes stomias</i>			†	†			
<i>Glyptocephalus zachirus</i>				*			
<i>Hippoglossoides elassodon</i>				*	*		
<i>Hippoglossus stenolepis</i>			†	¶	¶		
<i>Lepidopsetta bilineata</i>			†	¶	†		
<i>Reinhardtius hippoglossoides</i>				*			
<i>Salvelinus malma</i>					¶		§
<i>Trichodon trichodon</i>					†		
<i>Gymnocanthus pistilliger</i>					*		
<i>Radulinus asprellus</i>					*		
<i>Pallasina barbata</i>					*		
<i>Bathymaster caeruleofasciatus</i>						†	
<i>B. signatus</i>				†		†	
<i>Chirolophis nugator</i>						*	
<i>Sebastes ciliatus</i>						†	
<i>Hexagrammos decagrammus</i>						*	
<i>H. lagocephalus</i>	§	†			†	¶	†
<i>Blepsias cirrhosus</i>						†	
<i>Hemilepidotus hemilepidotus</i>			†		†	¶	
<i>Nautichthys pribilovius</i>						*	
<i>Triglops pingeli</i>						*	
<i>Agonus acipenserinus</i>				†	†	¶	
<i>Aspidophoroides bartoni</i>							
<i>Aptocyclus ventricosus</i>	†					†	§
<i>Crystallichthys cyclospilus</i>						*	
<i>Polypora greeni</i>						†	†
<i>Gasterosteus aculeatus</i>							†
<i>Anoplarchus purpureus</i>						†	¶
<i>Phytichthys chirus</i>						†	†
<i>Pholis dolichogaster</i>							*
<i>P. laeta</i>						†	¶
<i>Clinocottus acuticeps</i>						†	¶
<i>C. embryum</i>						†	†
<i>Liparis callyodon</i>						†	¶

*Uncommon in Amchitka waters.

†Infrequently encountered; seasonal or suspected (but undocumented) occurrence.

‡Frequently encountered.

§Abundant in juvenile life states.

¶Abundant; representative of this community.

invertebrates, many of which appear to be their major prey organisms. Several groups exist in the lower (150 to 330 m) strata of our sampling depth regime. The California headlightfish and the northern lampfish and their principal prey species, *Thysanoessa longipes*, *T. inermis*, *Euphausia pacifica* (euphausiids), *Sergestes similis*, *Hymenodora frontalis* (shrimps), and *Gonatus magister* and *Galiteuthis armata* (squids), occur with another fish group that is composed of the Pacific viperfish and the bigeye lanternfish and another invertebrate group of *Gonatus fabricii* (squid) and *Bolitaena heathi* (octopus). A fish-shrimp group of the pinpoint lampfish and *Notostomus japonicus*, an oplophorid shrimp, is defined for the deeper (220 to 330 m) strata, and an intermediate-depth (110 to 146 m) group of Pacific sand lance and tadpole snailfish is also designated.

Demersal fishes, such as the walleye pollock, appeared to enter the mesopelagic community when the planktonic scattering layers composed of euphausiids, shrimps, mysids, and squids migrated within their feeding range. Some of the species noted as being uncommon in the mesopelagic community may actually have been members of the epipelagic community which were captured during the movement of the midwater trawl through epipelagic waters. The occurrence of the Pacific lamprey, smooth lumpsucker, and rock greenling in this community may well be explained in this way. The Pacific lamprey, however, has been noted at depths of 300 to 400 m by Abakumov (1964) and may range through both communities.

Offshore Demersal/Rock-Sponge Community. What we originally described as one entity, the offshore/bottom community (Isakson et al., 1971), has since been redefined as two communities on the basis of expanded data from catches over two physically different deepwater bottom habitats. The habitat of the offshore demersal/rock-sponge community includes those areas adjacent to Amchitka which are rocky and rough bottomed, often with precipitous cliffs and pinnacles, and which form much of the bottom area between 55 and 180 m (180 and 590 ft) in depth on the southeastern side of Amchitka. The bottom material retrieved incidentally with the fishes during trawling included an abundance of sponge (family Axinellidae), coral (family Stylasteridae ?), and tunicates. Observations made while scuba diving over the extensive shoals indicate that the bottom (at least to 30 m deep) is also extensively blanketed by coralline algae (*Clathromorphum* spp.) (P. A. Lebednik, University of Washington, personal communication). The catches

were distinctly biased because only the least-rugged terrain was fishable by trawl nets. Echo-sounding tracings of the sidewalls of submarine canyons and pinnacles showed large aggregations of fishes that could not be sampled with our nets. Their behavior indicated that these fishes were rockfish (family Scorpaenidae, probably Pacific ocean perch) or walleye pollock. The most abundant schooling fishes of the offshore demersal/rock-sponge community were Pacific ocean perch, redstripe rockfish, Pacific cod, and walleye pollock. The most abundant bottom fishes were yellow Irish lord, blackfin sculpin, ribbed sculpin, spectacled sculpin, northern ronquil, roughtail skate, and arrowtooth flounder.

Bottom trawl catches from this community ranged between 200 and 1000 fish per hour, the higher catch rate occurring when schools of Pacific ocean perch, Pacific cod, or walleye pollock were encountered. Catch composition typically ranged from 40 to 900 Pacific ocean perch, 30 to 55 walleye pollock, 20 to 45 Pacific cod, 20 to 30 sculpins (family Cottidae), 6 to 12 arrowtooth flounders, 6 to 7 rock sole, 2 to 6 Pacific halibut, and 0 to 1 poacher (family Agonidae) per trawling hour. Lithodid crabs, predominantly *Lithodes aequispina*, were taken in many trawls, their catch averaging 4 to 9 crabs per hour with maximum catches of 40 to 50 crabs per hour.

Three groups of fishes were designated by the recurrent group analysis as existing within this community, primarily as found on the Pacific Ocean side of Amchitka. A cottid group, which includes the blackfin sculpin, the yellow Irish lord, and several *Triglops* species and associated with the northern ronquil and the lithodid crab (*Lithodes aequispina*), occurs dominantly in the 150- to 200-m depth region. The Pacific ocean perch and walleye pollock occur in association with the king crab (*Paralithodes camtschatica*) in deeper water (from 250 to 400 m) and a distinct rockfish group, which includes the rougheye rockfish and shortspine thornyhead, was found in the 220-m depth region.

The offshore community is vulnerable to disturbance, as indicated by replacement of rockfish by walleye pollock after fishing by foreign vessels in fall 1972 and spring 1973 (Nakatani and Burgner, 1974). If we assume that the Pacific ocean perch populations were cropped to low population levels by the fishing fleets [and had not just moved out of the area (Chikuni, 1975)], it appears that populations of walleye pollock, apparently a successful competitor, had succeeded the rockfish. After an extensive period for recruitment to build up its population again, the longer lived

Pacific ocean perch may eventually supplant the walleye pollock.

Offshore Demersal/Sand-Gravel Community. The offshore demersal/sand-gravel community is the assemblage of fishes common to the offshore low-relief expanses of silt, sand, and rock cobbles found between approximately 55- and 95-m depths in the Bering Sea north of the Milrow and Cannikin test sites on Amchitka (Fig. 1). There appears to be very little encrusting benthic growth, such as sponges, corals, and hydroids, although sea pens (family Virgulariidae) occur on the outer (deeper) margins of this habitat. Cobbles brought up in the trawling operation were often entirely covered by the coralline alga *Mesophyllum* sp., which suggests that the habitat's cobble substrate is relatively loose and perhaps not stable (P. A. Lebednik, University of Washington, personal communication). The diversity of the fish fauna comprising this community is lower than that in the other offshore bottom habitat. Catch composition in the offshore demersal/sand-gravel community ranged to a maximum of 320 rock sole, 94 Pacific halibut, 50 armorhead sculpins, 5 searchers, and 10 sturgeon poachers per hour of trawling effort. The stomach contents of top carnivores, such as the Pacific halibut (see following food-web section), from this community indicated that pelagic schools of Pacific sand lance also were common members of this demersal community. Unlike fishes of the other offshore demersal fish community, two fishes, Pacific halibut and rock sole, in this community are relatively mobile, their concentrations shifting about locally, probably for feeding. They also change depth seasonally; this movement is perhaps associated with spawning activity. In the Bering Sea northeast of Amchitka, Pacific halibut maintain denser schools during the winter, dispersing and migrating into the shallower waters in late spring (Novikov, 1964), and rock sole concentrations disperse during a late summer-fall feeding migration (Shubnikov and Lisovenko, 1964).

The recurrent group analysis indicated that a basic group of three species, the rock sole, Pacific halibut, and Pacific cod, existed in distinct association with two other species, the arrowtooth flounder and sturgeon poacher. The Pacific cod association with the Pacific halibut and rock sole, however, was more pronounced on the Pacific Ocean side of Amchitka than in samples from the Bering Sea habitat.

Inshore/Sand-Gravel Community. Like its offshore counterpart, the habitat occupied by the inshore/sand-gravel community consists of a

sand-gravel substrate that possesses little stabilized benthic growth. This type of habitat is prevalent in embayments, such as Constantine Harbor, South Bight, Cyril Cove, and Makarius Bay (Fig. 1), and occasionally occurs as narrow areas along the exposed coastline between kelp beds or reef promontories along the bottom of submarine canyons. In areas where rock pinnacles with associated abundant algal growth stand in the middle of a sand-gravel expanse, fishes of the two inshore subtidal communities often intermingle, especially at night. This may indicate the direct relationship between spatial heterogeneity of this habitat and the diversity of its resident fish community.

Pacific cod, walleye pollock, and Pacific halibut appear to be seasonal transients of the inshore/sand-gravel community; however, limited winter sampling precluded the determination of whether these are actual migratory movements. Cod and pollock are abundant from spring until mid-October. Pacific halibut occur commonly throughout the year except during January, February, and March when they apparently move offshore for spawning. Juvenile Pacific halibut and Pacific sand lance were observed regularly in nearshore waters year round. No significant recurrent groups were defined within this habitat.

Inshore/Rock-Algae Community. The inshore/rock-algae community is characterized by a diverse abundant assemblage of fishes intimately associated with the extensive algal growth dominating the rocky nearshore coast. Approximately 60 to 70% of Amchitka's shoreline is composed of exposed rock outcrops, cliffs, or flat-rock benches extending underwater as subtidal rock terraces out to depths of as much as 100 m (Gard, Chap. 2, this volume). Abundant submarine algal growth, such as encrusting corallines, species of fragile Rhodophyta, and various kelps cover these terraces; most conspicuous are the dense kelp beds of *Alaria fistulosa*, which sometimes extend to the 20-m depth contour (Lebednik and Palmisano, Chap. 17, this volume). *Alaria* contributes to the bottom habitat by its massive holdfasts and sporophylls and by its long fronds, which form a protective forest canopy reaching to the surface where the large floating blades form a microhabitat in themselves (Fig. 5). The kelp forest habitat may contribute the multilayered quality of a terrestrial forest that has been shown to influence bird species diversity through the vertical partitioning of niches (MacArthur and MacArthur, 1961; Cody, 1968; Orians, 1969). In addition to the luxuriant macrophytic growth, sessile benthic animals—sponges, bryozoans, anthozoans, and ascidians—

Fig. 5—*Alaria fistulosa* kelp bed (underwater photograph). Note school of pelagic fish.

encrust any firm rock substrate, which creates a bottom habitat of incredible diversity in form, texture, and color.

Associated with the algae for food and protection are abundant crustaceans, echinoderms, and molluscs. The benthipelagic* crustaceans [principally mysids (*Acanthomysis* sp.) and amphipods] were often found in extremely dense underwater swarms (Fig. 6).

These and other abundant invertebrate populations comprise a diverse array of food organisms available to the fishes frequenting the habitat (see later food-web discussion). The spatial heterogeneity of the entire habitat and the diversity of its algal growth and associated food resources are jointly responsible for an abundant diverse fish assemblage.

Representative species in the inshore/rock-algae community include the rock greenling, red Irish lord, northern ronquil, silverspotted sculpin, great sculpin, and dusky rockfish. Pacific cod were also captured in the inshore/rock-algae community habitat of the island's exposed coast, which they were assumed to have entered from the adjacent inshore/ or offshore/sand-gravel community. No recurrent groups were found in the inshore/rock-algae habitat samples with the use of the affinity index of 0.40.

This assemblage for the most part consists of sedentary bottom fishes; however, a few, notably the

dusky rockfish, silverspotted sculpin, and some of the less abundant liparid species, occupy the pelagic kelp bed canopy and near-surface microhabitats. Although the latter fishes move freely about the *Alaria* blades and surface canopy either singly (silverspotted sculpin and liparids) or in schools (dusky rockfish), the bottom-associated fishes appeared restricted to a particular site. Scuba observations indicate that during daylight these fishes seldom move beyond the protection of the dense bottom algal cover, but at night they are seen among the benthipelagic swarms of mysids and amphipods.

The trammel net was the most productive sampling gear used in the inshore/rock-algae habitat. Sets of short duration, which avoided net saturation, yielded up to 36 fish of mixed species per hour, which averaged 75 to 80% rock greenling with the remainder red Irish lord, sturgeon poacher, Pacific cod, northern ronquils, and great sculpins. Dusky rockfish move in schools and were not consistently encountered; but, when they were encountered, they made up a significant proportion of the catch. Silverspotted sculpins and liparids were captured with surface plankton net tows through the *Alaria* fronds and were observed during scuba dives. During the winter, when the *Alaria* lose many of their surface fronds from wave

Fig. 6—Mysid, *Acanthomysis* sp., swarms in *Alaria* kelp bed (underwater photograph).

*Associated with bottom but rising pelagically off it.

action, the kelp forest is greatly thinned, and the pelagic fishes descend into the sublittoral fringe zone and its lush *Laminaria* growth. Other species, such as the dusky rockfish, also move from their summer habitat into deeper water during the winter, perhaps to avoid wave action or to follow their food resources.

The bottom-associated fishes are cryptically colored to resemble the reds and browns of the bottom habitat's flora and fauna. Even the distinctive silverspotted sculpin, which swims freely amidst the kelp fronds, is difficult to tell from a shred of algae when observed within its habitat. The male rock greenling, unlike the female, is marked with bright red bars that possibly are associated with reproductive or other social behavior. Although not so well camouflaged, it nevertheless blends well with the red algae of the understory. The rock greenling, red Irish lord, and sturgeon poacher are further concealed by their remaining motionless on the bottom supported by their broad pectoral fins. The suction disk on the ventral surface of liparids enables these small fishes to adhere to kelp fronds in the constant wave motion of the exposed kelp beds.

The rock greenling is by far the most abundant and widely distributed number of this community. This observation stimulated a detailed study of its life history, especially its feeding ecology (Simenstad, 1971a). Scuba observations indicate that adult rock greenling are territorial all months of the year and especially so during the spawning and incubating periods of late spring and early summer. The eggs are laid in purple masses that adhere to algae (usually *Laminaria* sp.) in the sublittoral fringe zone and are guarded by both the male and female. Even during incubating and nonspawning periods, individuals appear to maintain their established homesites, to which they return and rest after brief feeding forays.

Out of about 910 rock greenling in tagging studies, none of those recaptured moved along the shoreline more than 75 m (Burgner et al., 1971a). Simenstad (1971a) suggests that at high tide, especially at night, rock greenling leave their territories to forage on the invertebrate community of the littoral bench. The results from tagging imply that such departures for feeding are merely temporary excursions.

After the juvenile rock greenling hatch in the summer, they form pelagic schools and apparently move into offshore oceanic waters and into the epipelagic community. Although juvenile rock greenling were seldom captured in Amchitka's inshore waters, the purse seine catches of FRI's research vessels 65 to 95 km (40 to 60 miles) off

Kagalaska Island, 290 km (180 miles) east of Amchitka, often included significant numbers of juvenile rock greenling. After 2 to 3 years, they apparently migrate back into the inshore areas and become solitary (Gorbunova, 1962; Simenstad, 1971a). This unquantified observation suggests random recruitment from the rock greenling stocks of the whole Aleutian archipelago. Rock greenling food habits and feeding ecology are discussed in more detail in the following section on food webs.

Littoral Community. The littoral fish community is that assemblage of fishes characteristic of the surge channels and tide pools of the rocky littoral bench that typifies much of Amchitka's shore (Fig. 7). Although this assemblage can logically be considered a shallow-water extension of the inshore/rock-algae community, it can be distinguished from that community by the presence of distinctive species. This habitat also provides a nursery ground for juvenile fishes.

This community was most often sampled at low tide; so the entries of Table 3 do not completely represent the community at high tide when species undetected in our sampling could have been present. Littoral-occurring fishes were collected with the use of rotenone in the tide pools (see method discussed by Wilimovsky, 1964), by hook-and-line fishing at high tide, and by setting gill nets on the littoral bench through a tidal cycle. As noted by Wilimovsky (1964) and generally confirmed in our sampling, the fishes of the littoral community responded to the rotenone sequentially according to their oxygen demands. We found that, after rotenone had been applied to a tide pool, fish succumbed in the following order: (1) silverspotted and great sculpins (the smaller specimens responded later), (2) sharpnose sculpins, (3) spotted

Fig. 7—Littoral bench at Rifle Range Point, Amchitka Island, Alaska. Note tide pools connected to sea by surge channels. Visible bench here averages 150 m in width.

snailfish and lobefin snailfish, (4) smooth lump-suckers, (5) ribbon pricklebacks and high cockscombs, and (6) northern ronquils. The response behavior also varied between species, as with the liparids, which habitually swam to the tide-pool surface, in contrast to the rock greenling, which swam excitedly among the algae at the bottom of the pool and eventually died there. Such varied behavior and response rate may have biased the collection; however, an effort was made to obtain and record every fish in a treated tide pool.

The recurrent group analysis indicated a single group of littoral fishes, which included the crescent gunnel, high cockscomb, ribbon prickleback, juvenile great sculpin, sharpnose sculpin, and spotted snailfish. During high-tide periods when the littoral bench is flooded, adult rock greenling and anadromous Dolly Varden also cruise over the bench, feeding on the mysids, amphipods, and other macroinvertebrates exposed or brought in with the flooding tide.

Species richness was greatest during the summer season, at which time the common-resident littoral fishes were the high cockscomb, crescent gunnel, sharpnose and silverspotted sculpins, and spotted snailfish. In the few large tide pools or surge channels, adult rock greenling were also found in abundance, especially during the June to August spawning period when they laid their eggs among the *Laminaria* in the sublittoral fringe zone. In the spring juvenile great sculpins began appearing in profusion in the littoral area and remained until fall before migrating off the bench. These small juveniles constituted up to 55 to 85% of all fish found in the midsummer tide-pool population. Similarly, juvenile smooth lump-suckers, Dolly Varden, coho salmon, and rock greenling were also abundant periodically during the summer according to the size of the tide pool, extent of algal cover, proximity to freshwater streams, substrate type, and distance from the seaward margin of the bench. Fish densities in the tide pools averaged 98 fish (range, 20 to 250) per 3- to 6-m³ tide pool. Some of this variability in these catches undoubtedly was due to varying temperature, which is known to greatly influence the effectiveness of the rotenone. Reduction of the littoral algal cover and of available prey resources as well as the reduced effectiveness of rotenone in colder waters were factors contributing to the low numbers and diversity of fishes encountered during the winter months.

Amchitka Marine Food Web

Some knowledge of the food-web structure in the marine ecosystem was deemed necessary to

serve the primary objective of our investigations, i.e., prediction of the potential consequences of a nuclear test or tests on Amchitka. Test-induced changes in the organizational structure of the marine food web, direct or secondary, could conceivably result from loss of habitat or from loss or change in numbers of important prey or predator species. Also, the food web is a potential route for transfer of radionuclides through the ecosystem and ultimately to man in the event of a release of radioactivity to the environment. Food-web studies were therefore undertaken to identify prey organisms of Amchitka marine fishes that (1) are most universally exploited throughout the food web, (2) have a major role in energy transfer or conversion, and (3) import significant amounts of energy into the food web from the high seas around the island.

Results of preliminary food-web analyses were presented in Burgner et al. (1969; 1971a), Burgner and Nakatani (1972), Nakatani et al. (1973), Nakatani and Burgner (1974), and schematically in Isakson et al. (1971), wherein the trophic interactions among fish communities and other exploiters (marine mammals, littoral-feeding birds, and man) were shown. In a practical sense, a relatively simple schematic cannot adequately display such complex relationships. However, it is possible to diagram the major trophic pathways and significant prey resources available to the upper-level components of the ecosystem. These aspects of the marine fish communities of Amchitka are shown in Figs. 8a and 8b. Although these figures are constructed from actual data, each link in the web represents an average derived from all samples, often collected over several seasons, including daytime and nighttime collections, and a range of predator sizes. This schematic model, a simplified condensed representation of the upper level of a very complex trophic structure, indicates the dominant members of the Amchitka fish communities relative to their more significant connections to other fishes and to the prey components of the system.

Although we detected some seasonal and year-to-year variations in the food habits of a few species, the limited extent of winter sampling and the small number of years of sampling preclude the incorporation of such variations into our model. Where appropriate, we have connected prey organisms to several predators. Although these predators may use common prey resources, this does not necessarily imply competition among these fishes for the same populations of prey or movement into adjacent communities for their exploitation. For many prey taxa (amphipods, shrimp, cephalopods, molluscs, and copepods), these general categories

EPIPELAGIC

MESOPELAGIC

OFFSHORE DEMERSAL / SAND-GRAVEL

OFFSHORE DEMERSAL / ROCK-SPONGE

Fig. 8a—Offshore epipelagic, mesopelagic, demersal/sand-gravel, and demersal/rock-sponge fish communities illustrating semiquantitative food-web relationships.

Fig. 8b - Inshore intertidal, rock-algae, and sand-gravel fish communities illustrating semi-quantitative food-web relationships.

include many diverse species representing different populations, niches, microhabitats, and/or behavior; it was impossible to determine, much less to indicate, where or how a fish captured any specific prey since we know little of each prey organism's distribution and behavior.

Frequency of occurrence of prey items (Table 4) provides an index of a fish's actual exploitation of the prey complementary to the biomass—percentage of total stomach contents indicated in Figs. 8a and 8b. The two kinds of information together show the trophic relationships among the components of Amchitka's marine fish communities.

Marine fishes in the littoral region rely on the diverse invertebrate communities associated with the extensive algal growth of that habitat. Especially in this habitat, the amphipod populations provide the major source of trophic energy to the littoral fishes and high-tide immigrants from adjacent communities. These amphipod populations reach high densities in the littoral area during the summer when the windrows of detached kelp and other algae piled on the beaches during the winter storm period contribute a tremendous source of detritus used by these crustaceans. The usually sedentary territorial character of many of the littoral fishes would restrict them to the food resources within their microhabitat or those which drift into it. With this restriction it is possible that they preferentially exploit the abundant "renewable" prey resources, the shifting amphipod, harpacticoid copepod, and drift insect populations, which pass through their territory. Most of the fishes that feed as specialists on these dense but patchy swarms of organisms make very limited use of the epibenthic invertebrates of this habitat. Thus the sedentary invertebrates are not heavily exploited except by the high cockscomb, lobefin snailfish, and that mobile forager from the adjacent inshore/rock—algae community, the rock greenling.

The diet and feeding ecology of the rock greenling, the most abundant fish of Amchitka's inshore marine environment, were the focus of an intensive study (Simenstad, 1971a). As an opportunistic feeder the rock greenling exploits the diverse community of macroinvertebrates found in abundance in the inshore/rock—algae and intertidal habitats. The fact that its stomach contains organisms from both littoral and inner sublittoral habitats suggests that the greenling move over the littoral bench during high tide for feeding. Although the adult rock greenling is not typically a free-swimming schooling species, schools of this fish (often only males) were observed foraging over the bench, often rising to the surface and making

"rippling—popping" sounds (Simenstad, 1971a). They were swimming across the bench picking up benthic macroinvertebrates—gastropod and bivalve molluscs, amphipods, isopods, and polychaete annelids—when they were encountered.

Instead of confining their feeding to periodic intensive activity during the submersion of the intertidal bench, the greenling appear to forage to some degree continuously throughout the day and night. Although the greenling tend to feed slightly more during the day, at night they can safely leave the algal protection at the bottom and forage in the swarms of benthipelagic amphipods and mysids of the *Alaria* forest. Simenstad (1971a) suggested that, apparently because of the metabolic or survival cost of the uncertainty of encounter with the patchy swarms of crustaceans, the rock greenling maintain a generalistic feeding behavior until they encounter dense concentrations of amphipods or mysids. Then the fish feed on these crustacean swarms exclusively until satiation or until the crustaceans are too sparse to make it worth the effort. Simenstad considered predation pressures by the sea otter and other carnivores (Table 4) and maintenance of reproductive territories important factors in maintaining this feeding behavior. This pattern of feeding was often shown by rock greenling stomach contents, where homogeneous concentrations of mysids or amphipods were found preceded by or followed by a heterogeneous accumulation of ingested gastropods, isopods, and annelids. Similar feeding strategies have been discussed by Schoener (1969;1971), Rapport (1971), and Pulliam (1974) in their discussion of optimality theories in diet strategies.

Although none of the other dominant fishes of the inshore/rock—algae community are such generalistic feeders as the rock greenling, most also rely on the abundant benthic macroinvertebrates or benthipelagic crustaceans common to that habitat. Of these, the great sculpin and Alaskan ronquil seem to be the most opportunistic, the former being the only fish that is at all piscivorous; red Irish lords, sturgeon poachers, and searchers tend to be more specialist in their feeding preferences. The only fishes with a narrow range of choice in their diet are the pelagic fishes of the community, the dusky rockfish and silverspotted sculpin, which exploit solely the benthipelagic mysid and amphipod populations within the *Alaria* forest.

The smooth lumpsucker seems to exploit food resources throughout the water column from the shrimp and polychaete annelids associated with the bottom to the benthipelagic amphipod and mysid swarms beneath the *Alaria* canopy. This fish may once have been a dominant component of this

nearshore community, but apparently it was severely reduced in abundance by sea otter predation since it is an extremely sluggish species and not efficient at escaping a predator like the sea otter (*Enhydra lutris*). Fish collections made in the 1950s produced abundant catches of the smooth lumpsucker (Kenyon, 1969, and personal communication); our recent intensive sampling with similar methods seldom produced more than two of these fishes a year, one-twentieth of a day's catch of 20 years ago. That the lumpsucker still persists in the Amchitka nearshore environment, despite the intense sea otter foraging pressure, is a result of its reproductive strategy of producing hundreds of thousands of pelagic eggs per fish. Eggs comprised 41% of the total weight of a female captured in late April 1972! As a result juvenile smooth lumpsuckers are found in tremendous numbers in the littoral zone every spring. Guryanova (1935) also noted the abundance of this fish in the Commander Islands during the spring and summer.

In the inshore/sand-gravel community is a two-compartment food web, one oriented to the neritic fishes, the salmonids, Atka mackerel, and Pacific sand lance, and the other oriented to the bottom-associated fishes, the gadids, pleuronectids, armorhead sculpin, and Pacific sandfish. The prey organisms in the neritic compartment are planktonic crustaceans, hyperid amphipods (mostly *Parathemisto abyssorum*), mysids and copepods (*Calanus cristatus*, *Pseudocalanus elongatus*), and adult and larval Pacific sand lance. *Oikopleura* sp. (a larvacean) are heavily preyed on during infrequent periods of high abundance in the plankton. In addition, Dolly Varden and pink salmon in inshore waters occasionally take drift insects that have been blown out from the adjacent land mass.

Bottom-associated fishes are almost all macrophagous. Prime examples of these are the Pacific halibut and Pacific cod. All but the rock sole are to some extent piscivorous in their diet. Partitioning of food resources among fishes of similar habitats is evident when the gadids and pleuronectid members of this community are compared. The Pacific cod is dependent on armorhead sculpins and mobile benthic crustaceans, shrimp, and the horse crab (*Erimacrus isenbeckii*), whereas the walleye pollock concentrates on mysids, with Pacific sand lance and rock sole providing incidental contributions to the diet. The rock sole is a benthophage that preys on polychaete annelids and benthic amphipods. The Pacific halibut is a higher order consumer that feeds principally on rock sole and Pacific sand lance and secondarily on squid, octopus, and the horse crab and two lithodid crabs,

Lithodes aequispina and king crab *Paralithodes camtschatica*. Armorhead sculpins rely predominantly on benthic amphipods and isopods and secondarily on polychaete annelids. These sculpins are somewhat opportunistic, as indicated by the dominance of *Oikopleura* in their diet during an abnormally high occurrence of these larvaceans in the inshore waters in August 1969.

The diets of the demersal fishes in the offshore portions of the sand-gravel habitat show some interesting differences from their inshore diets in those species common to both (Table 5). Offshore-caught rock sole consumed more ophiuroids than polychaete annelids and amphipods but there are fewer ophiuroids in nearshore areas. Skalkin (1963) and Shubnikov and Lisovenko (1964) indicated that rock sole in the southeastern Bering Sea depend on polychaetes and molluscs as their major food items, with crustaceans, Pacific sand lance, and echinoderms of secondary importance. This may reflect, in effect, differences in the benthic macrofauna associated with this habitat in the two regions. Offshore Pacific halibut prey on walleye pollock, armorhead and other unidentified sculpins, and sturgeon poachers rather than on Pacific sand lance and rock sole, even though the latter occur abundantly in this habitat. This apparent selectivity also occurred in this species' predation on decapod crustaceans, primarily horse crabs and shrimp, although king crabs appear to occur in equal abundance. The reason that rock sole and king crab were not preyed on is not apparent. The diet composition of offshore halibut was similar to that found by Gordeeva (1954) and Novikov (1964) in the western, northwestern, and central Bering Sea, where fishes (pollock, smelts, eelpouts, Pacific herring, and Pacific sand lance) and crustaceans [spider crabs (*Chionoecetes*?), fiddler crabs, hermit crabs, and shrimp] are the primary prey and molluscs (octopuses) are secondary. A trend of changing diet composition by size, as noted by Novikov (1964), was also indicated at Amchitka—increasing dependence on fishes and molluscs and decreasing emphasis on crustaceans with increasing fish size (30 to 60 cm to 790 cm). If one considers the Pacific sand lance to be the western Aleutian ecological equivalent of smelt and herring, the diets of halibut throughout the Bering Sea are very similar. Even with a small sample size, the indications are that nearshore the halibut much prefers to eat amphipods (primarily bottom species) whereas offshore it is more piscivorous. The arrowtooth flounder, not found nearshore, appears to divide its diet between shrimp and an unidentified cottid, possibly the armorhead sculpin; again this is an inference from a small sample.

		Prey items																															
Fish community	Fish species	Lithodid crabs, <i>Lithodes</i> , <i>Paralithodes</i> , and <i>Haplogaster</i>	All decapods, including unidentified	Gammarid, caprellid, and hyperiid amphipods	Mysids	Calanoid and harpacticoid copepods	<i>Stenobrachius</i> <i>leucopsarus</i>	<i>Ammodytes</i> hexapterus, including larvae	<i>Bathylagus stibius</i>	<i>Nectoliparis pelagicus</i>	<i>Chauliodus macouxi</i>	<i>Electrona arctica</i>	<i>Gadus macrocephalus</i>	<i>Theragra chalcogramma</i>	<i>Bathymaster</i> sp.	<i>Anoploarctus purpurascens</i>	Unidentified cottids	<i>Blepsias cirrhosus</i>	<i>Clinocottus</i> sp.	<i>Gymnocanthus galeatus</i>	<i>Hemilepidotus</i> <i>hemilepidotus</i>	<i>Myoxocephalus</i> <i>polyacanthacephalus</i>	<i>Sebastes</i> sp., including juveniles	<i>Clupea harengus pallasii</i>	<i>Agonus acipenserinus</i>	<i>Hippoglossus stenolepis</i>	<i>Lepidopsetta bilineata</i>	<i>Hexagrammos lagocephalus</i>	<i>Aptocyclus ventriosus</i>	<i>Eumicrotremus orbis</i>	<i>Liparis</i> sp.	All fish, including unidentified	
Epipelagic	<i>Oncorhynchus keta</i>			11		11																										11	
	<i>O. nerka</i>			80			20																									20	
Mesopelagic	<i>Alepisaurus ferox</i>																				50				50						50	100	
	<i>Bathylagus stibius</i>					38																										13	
	<i>Chauliodus macouxi</i>			25																													
	<i>Diaphus theta</i>			24		35																											
	<i>Electrona arctica</i>			25		25																											
	<i>Stenobrachius leucopsarus</i>		2	5		51																											
	<i>Coryphaenoides acrolepis</i>		25			50		50			25	25	25																				100
Offshore demersal/ rock- sponge	<i>Gadus macrocephalus</i>		100	25				25														50											75
	<i>Theragra chalcogramma</i>		9	32			5		5															5									32
	<i>Sebastes alutus</i>					40																											8
	<i>Hemilepidotus hemilepidotus</i>			83	50																												
	<i>Mallacocottus kincaidii</i>	6	28	61																													
Offshore demersal/ sand- gravel	<i>Myoxocephalus polyacanthacephalus</i>	50	100														6																25
	<i>Bathymaster signatus</i>																																100
	<i>Atheresthes stomias</i>		25	25													25																25
	<i>Hippoglossus stenolepis</i>		53	16										2			4			5													68
Inshore/ sand- gravel	<i>Lepidopsetta bilineata</i>			29																													
	<i>Oncorhynchus gorboscha</i>			77	41			5																									45
	<i>Salvelinus malma</i>			50	48			12																									27
	<i>Gadus macrocephalus</i>		47	51	27	2		7												19	4			3									75
	<i>Theragra chalcogramma</i>		13	35	90	13		2																									21
	<i>Trichodon trichodon</i>			44	67			11																									11
	<i>Ammodytes hexapterus</i>			100		100																											
	<i>Pleurogrammus monopterygius</i>		12	36	48	30		3																									10
	<i>Gymnocanthus galeatus</i>		4	55	18	1		4																									17
	<i>Hippoglossus stenolepis</i>	6	32	20	3			29						7	3			3		1	7						1	22					74
	<i>Lepidopsetta bilineata</i>		6	88	6																												
	<i>Bathymaster caeruleofasciatus</i>			67																													
	<i>B. signatus</i>			100																													
	<i>Sebastes ciliatus</i>			40	60	10		5																									
	Inshore/ rock- algae	<i>Hexagrammos lagocephalus</i>		7	83	19	3									1	1		1	1			1	1					1				1
<i>Blepsias cirrhosus</i>				100	25																												12
<i>Hemilepidotus hemilepidotus</i>			19	80	8	2		1					1				7			1	3	1						1					25
<i>Myoxocephalus polyacanthacephalus</i>				89				3													1	3	1										11
<i>Agonus acipenserinus</i>			33	100	7																					1							13
<i>Aptocyclus ventriosus</i>			75	100	25																												50
<i>Polypera greeni</i>			50	100																	3												50
<i>Anoploarctus purpurascens</i>				50																													
<i>Pholis laeta</i>				100																													
<i>Clinocottus acuticeps</i>				100																													
Intertidal	<i>C. embryum</i>			33		100																											
	<i>Liparis calyodon</i>			100				13																									

*Includes nonquantitative observations.

Table 5—Percentage Composition by Biomass and Percentage Occurrence (in Parentheses) for General Prey Taxa of Important Species Occurring in Both Offshore and Inshore Communities

Predators	No.	Prey						
		Fish	Decapods	Molluscs	Amphipods	Mysids	Copepods	Miscellaneous
Pacific cod								
Offshore	4	85.5 (75.0)	10.8 (100.0)	0.1 (25.0)	0.4 (25.0)	0.0 (0.0)	0.0 (0.0)	3.2 (75.0)
Inshore	112	66.1 (76.8)	16.5 (48.2)	0.3 (8.9)	4.0 (51.8)	2.5 (27.7)	0.1 (1.8)	10.5 (58.9)
Walleye pollock								
Offshore	22	8.3 (31.8)	86.8 (95.5)	2.6 (13.6)	2.2 (31.8)	0.0 (0.0)	0.0 (0.0)	0.1 (4.6)
Inshore	48	14.6 (20.8)	0.7 (4.2)	0.0 (0.0)	10.5 (35.4)	70.8 (89.6)	2.7 (12.5)	0.7 (6.3)
Great sculpin								
Offshore	4	0.0 (0.0)	100.0 (100.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
Inshore	37	55.2 (10.8)	0.0 (0.0)	0.1 (2.7)	34.3 (89.2)	0.0 (0.0)	0.0 (0.0)	10.4 (51.4)
Red Irish lord								
Offshore	6	0.0 (0.0)	72.0 (83.3)	0.0 (0.0)	8.9 (50.0)	0.0 (0.0)	0.0 (0.0)	19.1 (50.0)
Inshore	110	10.8 (24.5)	18.9 (19.1)	2.7 (16.4)	39.0 (80.0)	0.5 (8.2)	0.0 (0.0)	28.1 (67.3)
Pacific halibut								
Offshore	57	64.9 (68.4)	31.9 (52.6)	0.8 (3.5)	0.2 (15.8)	0.0 (0.0)	0.0 (0.0)	2.2 (17.5)
Inshore	69	68.1 (74.0)	24.6 (31.9)	4.7 (14.5)	0.2 (17.4)	* (2.9)	0.0 (0.0)	2.4 (21.7)
Rock sole								
Offshore	4	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	100.0 (100.0)
Inshore	16	0.0 (0.0)	3.9 (6.3)	0.2 (6.3)	15.9 (87.5)	0.2 (6.3)	0.0 (0.0)	79.8 (87.5)

*Less than 0.05%.

The offshore demersal/rock-sponge community includes four fishes that are also found in inshore communities: (1) Pacific cod, (2) walleye pollock, (3) great sculpin, and (4) red Irish lord (Table 5). Cod inshore and offshore are equally piscivorous, but offshore they feed exclusively on red Irish lord and Pacific sand lance whereas inshore they prey on armorhead sculpins more than on any other fish. Inshore, shrimp were prominent in their diets, and squid and octopus had replaced *Erimacrus*. Pacific cod in both inshore and nearshore habitats seem not to exploit the abundant benthopelagic amphipods. Although walleye pollock in the offshore community appear to be characteristically associated with the Pacific cod and sculpins along the bottom, benthic organisms are not dominant in their diet. Instead, the walleye pollock apparently move up off the bottom diurnally to exploit mesopelagic euphausiids (contributing 87% of the stomach contents biomass), shrimp, squid, octopus, and fishes (northern lamp-

fish, California smoothtongue, and juvenile rockfish, *Sebastes*).

Offshore cottids also differ from their inshore counterparts in their food habits (Table 5). Red Irish lord feed selectively on horse crabs with supplemental contributions by shrimp, amphipods, and polychaete annelids. Large adult great sculpins feed exclusively on the two large decapods, the horse crab (*Erimacrus*) and the tanner crab (*Chionoecetes* sp.). The blackfin sculpin, an abundant cottid exclusive to this habitat, is a benthophage that preys on polychaete annelids, ophiuroids, bivalves, gastropods, squid, octopus, deepwater isopods (*Arcturus setulosus*?), horse and tanner crabs, amphipods, shrimp, and unidentified cottids, the more important prey being polychaete annelids, amphipods, and the fishes.

The dominant fish of the deepwater rockfish niche, the Pacific ocean perch, is planktivorous, concentrating on the euphausiid (86% composition by weight) and hyperiid amphipod (6% composi-

tion by weight) components of the coastal zooplankton with incidental exploitation of mesopelagic fishes—Pacific viperfish and lanternfishes—and demersal cottids. A large bathypelagic calanoid copepod (*Calanus cristatus*) and the chaetognath [*Sagitta planctonis* (?)] also appear in the Pacific ocean perch diet. This diet composition generally agrees with the findings of Lyubimova (1963), Paraketsov (1963), Skalkin (1964), and Chikuni (1975), who found crustaceans to be the major prey items with planktonic [calanoids (*C. cristatus*), euphausiids, and hyperiids] and nekto-benthic (mysids, amphipods, and shrimps) organisms predominating. These investigators also found some squids and small fish in the rockfish stomachs.

Mesopelagic fishes include planktivorous lanternfishes and bathylagids and their predators, the Pacific viperfish and roughscale rattail. Calanoid copepods and hyperiid amphipods constitute the major food sources of the lanternfishes with supplemental input from euphausiids (*Thysanoessa longipes*, *T. inermis*, and *Euphausia pacifica*), chaetognaths (*Sagitta* sp.), squid and pteropods, and carid shrimp (*Sergestes similis*). The viperfish and rattail prey selectively on the northern lampfish, the most abundant lanternfish of that fish community. The roughscale rattail also preys on its smaller competitor, the Pacific viperfish, and mesopelagic mysids (*Gnatophausia gigas*), isopods (*Arcturus* spp.), euphausiids, and squid (*Galiteuthius armata*). California smoothtongue prey on chaetognaths and calanoid copepods with a secondary contribution from euphausiids.

The maturing migrating sockeye and chum salmon of the epipelagic community are primarily piscivorous, preying on both the forage fish resident in that community (the Pacific sand lance) and the planktivorous northern lampfish of the adjacent mesopelagic community; the sockeye salmon probably captures these lanternfish during that prey's diurnal migration into the upper regions of the deeper habitat. Hyperiid amphipods and calanoid copepods contribute to the diets of both species of salmon, calanoid copepods being an important secondary component (25% composition) of the chum salmon diet. The piscivorous feeding habits of Amchitka's sockeye and chum salmon may well reflect the patchy seasonal abundance of fish [especially myctophids (lanternfishes)] occurring in the upwelling area of the offshore waters. Previous investigations (Andrievskaia, 1957; Allen, 1956a; 1956b; Foerster, 1968; Le Brasseur, 1959; and Synkova, 1951) have shown that the most common components in the diets of these salmon in the western

Aleutians are euphausiids, hyperiid amphipods, and calanoid copepods with fish and squids forming only secondary food resources, indicating their seasonal patchy distributions around the North Pacific. Allen (1956b) further indicates that, where food is most abundant, both species become more selective in the feeding habits.

Longnose lancetfish are oceanic alepisaurids and were represented in the Amchitka collection by two fish that were blown ashore during stormy weather. Their stomach contents indicated that these fish are omnivorous predators that range through the epi- and mesopelagic water column and deeper, feeding on nekton resembling in composition that captured in our midwater trawling. Prey specifically includes Pacific spiny lump-suckers, octopus (*Bolitaena heathi*), and squid (*Gonatus* sp.). Other minor components include polychaete annelids, Pacific herring (*Clupea harengus pallasi*), and juvenile cottids, possibly red Irish lords. This diet composition indicates that the longnose lancetfish feeds opportunistically on the slow-moving components of the nekton, neglecting the abundant but more mobile lanternfishes and other forage fishes (Pacific sand lance and juvenile hexagrammids) as well as the dense zooplankton populations, all apparently available within the fish's habitat. This conclusion conforms with Haedrich (1964), Haedrich and Nielson (1966), and Parin, Nesis, and Vinogradov (1968). Parin et al. described these fish as feeding at depths of 100 to 300 m, at the boundary of the epi- and mesopelagic regions. This depth in the Indian Ocean is in the lower levels of the upper isothermal layer and the upper levels of the principal thermocline.

Without a more thorough knowledge of the distributions and abundances of the prey organisms or quantitative evaluation of predator exploitation, a complete summary of the dynamics of the trophic relationships between the components of Amchitka's marine food web is not possible. Given the first-order semiquantitative results of these investigations, however, some important generalizations can be made.

The nearshore environment harbors a rich diverse community of marine organisms providing abundant food resources to resident and immigrant fishes. This is, in part, a result of the diverse macrophytic algal flora of the Amchitka littoral and inner sublittoral zones. The intricacy of this community appears to be in response to the predation pressure on herbivores from the system's top carnivore, the sea otter (Palmisano and Estes, Chap. 22, this volume). This complex algal community not only provides a diversity of habitats for benthic and benthipelagic macroinvertebrates but also provides considerable autotrophically accumu-

lated energy to the inshore marine food web through linkages to the abundant herbivorous molluscs, echinoderms, and crustaceans. Direct herbivory, however, is not as significant a mechanism of energy transfer in this system as indirect herbivory, as was indicated by the low trophic contributions of herbivorous organisms to inshore fish. Even the opportunistic benthophagous rock greenling fail to prey significantly on herbivores in areas where other prey are abundant. Specifically, the major herbivore of the system, the sea urchin (*Strongylocentrotus polyacanthus*) occurs only incidentally in fish diets. Again, the effect of sea otter predation on the inshore sea urchin populations is to severely limit the availability of urchins to other inshore predators (Palmisano and Estes, Chap. 22, this volume).

On the other hand, indirect energy transfer through the production of detritus does appear to be significant. Seasonal die-off and attrition, especially during the winter storm period, create large masses of detached macroalgae in the upper littoral region. Their decay releases great quantities of detritus and nutrients into the inshore waters and promotes prodigious amphipod and mysid populations in the inshore habitats. The trophic importance of these benthopelagic macroinvertebrates in the food web is evident. Amphipods contributed a mean 39% by weight to the diets of the 25 inshore fish, and their mean frequency of occurrence was 72%; mysids, not as widely distributed as the diverse amphipod taxa, contributed 13% by weight and 20% in frequency of occurrence. Energy transfer through breakdown of macroalgae is not limited to inshore amphipods and mysids. Palmisano and Estes (Chap. 22, this volume) indicate that kelp fragments collect around *Hedophyllum* holdfasts and thus provide detrital food supplies to the special communities of invertebrates associated within and under the holdfasts, especially the isopods *Idotea wosnesenskii* and *Exosphaeroma amplicauda*, which also contribute to the diets of rock greenling and great sculpin. Simenstad (1971a) suggested that inshore-offshore circulation along the bottom carries detached intertidal algae from the littoral bench into inner sublittoral habitats where fishes prey both on littoral invertebrates carried with this algae and on those sublittoral forms foraging on the algae. It was also demonstrated that the decaying masses of algae in the upper littoral zones support heavy populations of beach fly (*Diptera* sp.) larvae which are then available at high tides to foraging rock greenling, spotted snailfish, and Dolly Varden.

The pelagic trophic equivalent of the amphipod is the Pacific sand lance. Although this fish

constitutes an unpredictable rapid-swimming resource, it contributes to the diets of 8 of the 10 species studied from the inshore/sand-gravel community. Its larval and prejuvenile forms are also in the diets of three fishes of the inshore/rock-algae community. This forage fish is the system's main means of energy transfer between zooplankton and the piscivorous fishes of the community. No predator can afford to prey selectively on sand lance since its occurrence is apparently not certain enough to guarantee a reliable food resource. However, when it does occur, it appears to be the selected preferred prey. Stomachs of predators were found to be unusually distended with sand lance whenever their schools were in the inshore waters. Even the rock greenling was observed to capture sand lance to distention during a large inshore influx of schools of sand lance in August 1973. Studies of the avian predators of Amchitka inshore fish have also noted the occurrence of sand lance in the diets of many species (Williamson, Emison, and White, 1972). Offshore the sand lance appears to suffer little predation pressure from epipelagic piscivores.

The relative importance of various components of the Amchitka inshore and offshore marine ecosystems can be further seen by enumerating and weighting the food-web links identified in Fig. 8. Table 6 shows the number of trophic contributions (arrows in Figs. 8a and 8b) in each of four categories of percentage relative biomass; the four percentage categories are weighted and added to provide a total weighted contribution of this prey to the ecosystem's fishes. Organisms in the 0 to 24% column were weighted 1, those in the 25 to 49% column were weighted 2, etc. Theoretically, in this simplistic approach the higher the total weighted contribution, the greater the role these prey resources play in the structure and energy-flow dynamics of the ecosystem. As indicated in Table 6, the most significant contributors are amphipods, mysids, polychaete annelids, and Pacific sand lance in the inshore ecosystem and amphipods, copepods, euphausiids, and northern lampfish in the offshore ecosystem.

Spatial heterogeneity of the habitats studied influences not only the structure of the associated animal communities but also the complexity of the food web involved. The homogeneous epipelagic portions of both offshore and inshore habitats have much simpler patterns of trophic links between the fishes and their food resources than the spatially heterogeneous inshore/rock-algae or offshore demersal/rock-sponge communities. This is assumed to be a result both of the greater diversity of food resource available in the heterogeneous

Table 6—Trophic Contributions by Percentages of Relative Biomass and Total Weighted Contributions of Prey Organisms to Inshore and Offshore Amclutka Marine Fishes

Prey organisms	Contribution and weighting factors*				Total	Weighted contributions
	0 to 24% (1)	25 to 49% (2)	50 to 74% (3)	75 to 100% (4)		
Inshore						
Amphipods	6	9	3	4	22	49
Mysids	2	4	3		9	19
Shrimps	4	1			5	6
Copepods	1			2	3	9
Isopods	3	1			4	5
Brachyuran crabs	2				2	2
Lithodid crabs	1				1	1
Cumaceans	1				1	1
Gastropods	3				3	3
Pelecypods	4				4	4
Amphineurans	1				1	1
Cephalopods	1				1	1
Ophiuroids	1	2			3	5
Polychaete annelids	7	1	1		9	12
Insects	3				3	3
Pacific sand lance	4	6			10	16
Armorhead sculpin		1	1		2	5
Rock sole	1	1			2	3
Red Irish lord		1			1	2
Offshore						
Amphipods	7	2			9	11
Mysids	1				1	1
Shrimps	5		1		6	8
Copepods	1	4	1	1	7	16
Isopods	1	1			2	3
Brachyuran crabs	1	1	2		4	9
Lithodid crabs	1		1		2	4
Euphausiids	5		1	1	7	12
Gastropods	1				1	1
Pelecypods	1				1	1
Cephalopods	5		1		6	8
Pteropods and heteropods	1				1	1
Ophiuroids	1			1	2	5
Polychaete annelids	1	2			3	5
Chaetognaths	2			1	3	6
Pacific sand lance		1	1		2	5
Armorhead sculpin		1	1		2	5
Red Irish lord	1				1	1
Northern lampfish	2	1		2	5	12
Pacific viperfish	2				2	2
Walleye pollock	1				1	1
Pacific ocean perch	1				1	1
California smoothtongue	1				1	1
Bigeye lanternfish	1				1	1
Pacific herring		1			1	1
Spiny lumpsucker	1				1	2
Sturgeon poacher	1				1	1
Tadpole snailfish	1				1	1
Unidentified cottids	1	1			2	3
Unidentified fish				1	1	4

*The factors used in weighting are given in parentheses.

communities and the concomitant more generalistic feeding behavior of the fishes there. The pelagic specialists (salmon, Pacific sand lance, and Atka mackerel) exclusively exploit the patchy abundance of planktonic prey, which enables them to maximize energy ingested per encounter with prey (copepods, pelagic amphipods, and mysids) concentrations.

The large specialist consumers of the demersal fish communities (great sculpins, arrowtooth flounders, and Pacific halibut) feed on large high-energy-per-item prey (fish and large crustaceans), which enables them to extract more energy per unit of feeding time than if they exploited the more common smaller prey available in their habitats (Schoener, 1969). The small specialists of the littoral community (pricklebacks and gunnells) feed on the abundant crustaceans. Their diets and opportunistic feeding behavior reflect the necessity for these species (small, territorial, and situated in a constantly fluctuating environment) to monitor prey, predators, competitors, and mates within a limiting habitat. Most of the generalists (rock greenling, red Irish lord, Pacific cod, walleye pollock, and blackfin sculpin) are species that occupy habitats with consistent heterogeneous concentrations of prey. These fishes are thus able to maximize energy consumed by feeding continuously on a diverse diet of prey organisms.

The benthipelagic amphipod and mysid populations appear to be the most universal prey and the principal converters of plant detritus energy into energy sources available to the secondary consumer level, and the offshore euphausiid populations play, to a lesser degree, a similar role; the principal energy importer apparently is the Pacific sand lance, the mobile populations of which continuously introduce energy derived from the zooplankton resources of the surrounding oceanic region into the Amchitka inshore ecosystem.

Other investigators (see Palmisano and Estes, Chap. 22, this volume) have documented the effect of the sea otter as a "keystone species" (Paine, 1969) and its herbivorous prey, the sea urchin, an influential "foundation species" (Dayton, 1972) in structuring the inshore biotic community. The role of this interaction, though indirect, in determining energy flow in the system's food web should not be ignored because it is the lower level conversion of energy that eventually determines the composition of the upper level consumers, such as the fish communities.

The lack of data on food sources of the prey organisms illustrated in Fig. 8 prevented us from extending corresponding linkages to lower trophic levels. Documentation of predation by Amchitka's

avian and mammalian top carnivores is similarly limited. Williams (1938), Murie (1940), Lensink (1962), Burgner and Nakatani (1972), and Palmisano and Estes (Chap. 22, this volume) all report predation on marine fishes by the sea otter at Amchitka. Kenyon (1969) specifically identified the smooth lump sucker, red Irish lord, Atka mackerel, and rock greenling as important constituents of sea otter diet at Amchitka in the 1960s, with the smooth lump sucker occurring most frequently in the stomachs examined. As noted earlier, predation pressure may have sharply reduced the abundance of this species in recent times.

Williamson, Emison, and White (1972) have reported fish predation by littoral and pelagic feeding birds, among them the Red-throated Loon (*Gavia stellata*), Pelagic Cormorant (*Phalacrocorax pelagicus*), Red-faced Cormorant (*P. urile*), Red-breasted Merganser (*Mergus serrator*), Bald Eagle (*Haliaeetus leucocephalus*), Glaucous-winged Gull (*Larus glaucescens*), Arctic Tern (*Sterna paradisaea*), Aleutian Tern (*S. aleutica*), Common Murre (*Uria aalge*), Thick-billed Murre (*U. lomvia*), Pigeon Guillemot (*Cephus columba*), Horned Puffin (*Fratercula corniculata*), and Tufted Puffin (*Lunda cirrhata*). The common prey of these birds was the Pacific sand lance, but the rock greenling, Atka mackerel, armorhead sculpin, red Irish lord, and spotted and lobefin snailfish were also represented in their diets. Pacific cod and rockfish species were also reported prey organisms, but it is suspected that these were scavenged from waste from a foreign fishing vessel offshore.

Impact of Amchitka Nuclear Tests on Marine Fishes

Principal interests of the U. S. Atomic Energy Commission in FRI's study of Amchitka's marine fishes were establishing pretest base lines of species occurrence and abundance and of ecological relationships so that posttest comparisons could be made to evaluate the impact of proposed underground nuclear tests at Amchitka. This information and information from the literature concerning shock effects were combined to provide inputs for the predictions and assessments by Battelle Memorial Institute and the AEC of the environmental impacts of the Milrow and Cannikin tests (Kirkwood, 1970; Merritt, 1970; Kirkwood and Fuller, 1971; 1972). In the establishment of these base lines, a great deal of new information was obtained about the marine fishes of Amchitka Island. This section summarizes the observed impact of the two tests (Milrow, Oct. 2, 1969;

Cannikin, Nov. 6, 1971) on Amchitka's marine fish communities.

A review of the literature from previous underwater explosions and related experiments or phenomena (Simenstad, 1971b; 1974) indicated that the shock wave from an underground nuclear explosion could inflict damage on marine organisms through several mechanisms. Directly, it could damage or kill individual organisms through the mechanical impact or pressure change produced when the shock wave passes through the water. It could also indirectly alter species composition, distribution, and/or abundance in the affected fish communities through the alteration of the marine habitat, which would affect changes in food resources, living space, and reproductive substrate. The hydrostatic changes imposed by the shock wave were considered, however, to be potentially the most damaging to individual fish. Two specific mechanisms are applicable in these circumstances: (1) Pressures over and under the ambient pressure and (2) bulk cavitation. The literature documents that, for low-frequency shock waves, such as those produced by the underground tests (10 to 15 Hz), the negative pressure phases of the hydrostatic pressure history would be the most damaging to fishes, more so to physoclistous* than to physostomous† and non-gas-bladdered species. Except for fast-rising shock waves incident on gas-bladdered fishes (as from dynamite explosions), compression or overpressure was not shown to be detrimental. A phenomenon that limits the maximum underpressure attainable, as a function of water depth, is cavitation, i.e., the reduction of pressure to the point of producing gas bubbles within the water. Cavitation of an organism's body fluids was thought to be an important mechanism of fish kill possible from the underground nuclear tests (Fig. 9). The observed effects of the Milrow and Cannikin events were evaluated with this background of direct and habitat-associated effects.

An underground nuclear test (Long Shot, Oct. 29, 1965) of 80 kt at Amchitka Island occurred prior to our investigations. A group of biologists from several organizations conducted surveys and experiments to evaluate the impact of this test on the fauna of Amchitka. Seymour and Nakatani (1967) reported no fish killed in live-boxes in the ocean as close as 1.6 km (Cyril Cove) to Long Shot surface zero (SZ).‡ The only dead

Fig. 9—Aerial photograph of marine waters surrounding test site during Milrow test, Oct. 2, 1969, approximately 1.5 sec after the detonation. Note white water areas which are regions of cavitation caused by shock wave produced by the underground nuclear detonation. (Photograph courtesy of Edgerton, Germeshausen and Grier, Inc.)

fishes observed were two Pacific cod in the waters off Cyril Cove. On the basis of the live-box experiments and the observed fish kill, the damage to fish life caused by Long Shot was judged insignificant (Seymour and Nakatani, 1967).

With the background of the Long Shot experience, in the summer of 1967 FRI began studies at Amchitka, including base-line surveys of existing fish populations for pretest and posttest comparisons of species composition and abundance of fishes, and live-box experiments were conducted at Milrow test time. Surveys continued after the 1969 Milrow test through the period of preparation for the Cannikin test in 1971 and continued thereafter until the spring of 1973.

Nakatani and Burgner (1974) and Isakson (1974) have reported on the impact of the Milrow and Cannikin tests on the overall marine environment. Burgner, Isakson, and Lebednik (1971b) summarized the impact of the Milrow test on Amchitka's marine environment, including fishes. We repeat the major findings below.

Milrow. Fish surveys were conducted both inshore and offshore before and after the Milrow test. Studies were concentrated on the Rifle Range Point—Duck Cove area (Fig. 1). Analysis of the catch-per-unit effort (fish per hour) before and after the test for all gear types used revealed no significant or marked changes in fish abundance offshore or inshore (Burgner et al., 1971a).

Immediately prior to the test, three pairs (six total) of live-boxes containing rock greenling and

*Possessing no pneumatic duct between the gas bladder and the alimentary canal.

†Possessing an open pneumatic duct between the gas bladder and the alimentary canal.

‡That place at the island's surface where the emplacement hole was started.

Fig. 10a—Predicted overpressure [in megapascals (pounds per square inch)] at bottom in Bering Sea adjacent to Cannikin SZ.

red Irish lord were placed in Duck Cove at distances from 2.6 to 4.0 km (8,500 to 13,000 ft) from Milrow SZ. These fishes were exposed to overpressures of 0.59 to 1.17 MPa (85 to 170 psi), underpressures of about -0.57 MPa (-83 psi), and accelerations of 2.5 to 5 g (Merritt, 1970; 1973). Other than two rock greenling, which apparently escaped, all fishes in the live-boxes survived. After the test these fishes were held for 4 weeks in seawater tanks and then released, no further or delayed injuries having been noted.

Three hours after the test, from a helicopter three unidentified and apparently injured fishes were seen thrashing on the ocean surface, two off Rifle Range Point, about 1.9 km (1.2 miles) southwest of Milrow SZ, and one off Crown Reefer Point, about 5.6 km (3.5 miles) north of Milrow SZ. These fishes could not be collected because the helicopter could not safely land. No other dead or injured fishes were seen during the posttest beach surveys.

Only rock greenling and red Irish lord were placed in the test-time live-boxes because they were the only species that survived the rigors of

capture for the Milrow holding experiments. The three injured fishes seen after the test may have been Pacific cod or rockfish, which possess gas bladders.

No accurate estimate of fish kill by Milrow is possible from such insufficient information. We believe there may have been a small kill of marine fishes, but it could have had little impact because it was not detectable in pretest and posttest comparisons. Indirect effects related to disruption of marine fish habitat were not detected.

Cannikin. After Milrow, sampling effort was shifted to the Bering Sea adjacent to Cannikin SZ. Locations ranged from Petrel Point to Crown Reefer Point and also included a second area adjacent to Kirilof Point and Kirilof Bay.

The sampling design included both test-time live-box experiments and pretest and posttest surveys in the areas where fishes were thought most vulnerable to pressure changes. Sampling and live-box positions were established with the use of maps of peak water-pressure changes (Figs. 10a and 10b) predicted to occur during the test. The theory

Fig. 10b—Predicted underpressure [in megapascals (pounds per square inch)] at the bottom in Bering Sea adjacent to Cannikin SZ.

and calculations behind these predictions resulted from the Milrow pressure-time data (Merritt, 1970; 1973; 1974; personal communication, 1971).

A severe storm, with winds of 110 km/hr, gusting to over 150 km/hr, throughout the day and night before the Cannikin test resulted in heavy seas, which prevented the placement of live-boxes as planned (Nakatani, Isakson, and Burgner, 1973, Appendix B; Isakson, 1974). Instead, 7.5 hr before the test a single live-box string was placed in 18-m (60-ft)-deep water in Constantine Harbor about 15 km (9 miles) from Cannikin SZ. A live-box at 16-m (52-ft) depth contained six rock greenling, four Pacific cod, three Pacific halibut, two red Irish lord, one rock sole, one great sculpin, and one dusky rockfish. Another live-box at 2-m (7-ft) depth contained 10 rock greenling and 6 Pacific cod. Three hours after the test, only one fish, a 67-cm (26 in.) Pacific cod, showed any abnormality, a "bubble" in the right eye and difficulty in equilibrium maintenance. Because no similar problems were seen in the other fishes, it was assumed that these symptoms were the result

of handling, possibly during cage retrieval, rather than a test effect. All experimental fishes and control fishes were held for 8 days after the test, and no delayed mortalities or injuries were noted in the experimental fishes.

Immediately after the test, no dead or injured fishes were seen from a helicopter or from a ship. However, viewing was poor because of heavy seas.

Beginning about 4 hr after Cannikin and during daylight hours for 3 days after the test, biologists from several organizations surveyed the Bering Sea and Pacific Ocean coasts adjacent to the Cannikin SZ area. The areas surveyed and the fishes recovered are shown in Fig. 11. Almost all the dead fishes found were stranded on tidal benches or beaches uplifted as much as a meter. Otherwise, owing to the northwesterly winds prevailing during the test, fishes washed up on the shore were found mostly on the Pacific Ocean side of Amchitka.

Of the 295 fishes recovered during beach walks, the majority (277) were rock greenling that were stranded on uplifted intertidal benches and washed into coves on sand and cobble beaches. Autopsies by Dr. Robert Rausch (U. S. Public Health Service,

Alaska) of 23 rock greenling revealed that about half had hemorrhaged or sustained other damage in the brain cavity and/or the viscera as the result of water-pressure changes, acceleration while over the littoral bench, or in struggling once the beach had lifted.* The other autopsied rock greenling exhibited no noticeable injury.

The Pacific sandfish were found stranded in uplifted sandy beach areas and in drift zones of Sand Beach Cove (Fig. 11). This species commonly burrows upright in the sand of the littoral zone, and the fish were probably stranded there by the beach uplift during the test. Since longnose lancetfish are often washed ashore after storms, the one specimen found after Cannikin is assumed to be a result of the pretest storm and not the test.

The remains of Pacific cod and rockfish found on the Pacific shore had been stripped nearly to skeletons by amphipods. Because both of these fish species are physoclistous, they were probably killed by water-pressure changes, and a portion of those which surfaced were blown onto the shore. Cannikin being nearer the Bering Sea, greater pressure changes (both in magnitude and in area) were predicted there than in the Pacific Ocean (Figs. 10a and 10b), which implies that cod and rockfish should have been recovered off the Bering Sea coast but were not as a result of wind direction.

The only other marine fish recovered dead after the test was a dusky rockfish taken 3 days after the test in a bottom trawl (Fig. 11, haul No. 33) at 40 m (22 fm) in the Bering Sea about 6 km (4 miles) from Cannikin SZ. One expects fish captured by trawl to be killed or badly injured, but pale gills, pale external coloration, and amphipod predation indicated that this fish had been dead for some time. The recovery of this one individual suggests that other fishes killed by Cannikin also sank to the bottom, which further reduces the fraction of fish recovered.

Echo-sounding traces from along the Bering Sea coastline adjacent to Cannikin SZ indicated that the large schools of fish (probably rockfish and Pacific cod) normally present around submarine pinnacles before the test were not present afterward. Unfortunately these observations cannot be translated into quantitative estimates of fish kill and only represent general impressions.

Offshore, only the bottom trawl catches of rock sole declined significantly when actual or

expected† posttest data were directly compared to pretest data for the same areas. The geometric mean catch of rock sole (average catch depth) significantly (t-test statistic, 2.52) declined from about 100 fish per hour pretest to a mean catch of about 31 fish per hour posttest. [See Nakatani et al. (1973) for further explanation of statistical catch comparisons.] Differences between Pacific halibut and total bottom trawl catches were statistically insignificant. Declines were observed for salmon species, Pacific cod, rockfishes (*Sebastes*), and midwater fishes, but occurrence and abundance of these species in the catches were too low to permit statistically valid comparisons of pretest and posttest catches. No decrease in catch of the more vulnerable physoclistous species (Pacific cod and rockfishes) was detected by this method, although the facts of dead cod having been found on the Pacific Ocean shore and greater pressure changes being expected on the Bering Sea side imply that some decrease might have been expected. This species is not a dominant of the fish community in the sampling area, however.

We estimate the size of the marine fish kill from Cannikin to be in the thousands (Kirkwood and Fuller, 1972), but such an estimate can be little more than a guess with the data collected. Even such an impact as this offshore fish kill on the marine environment was relatively small, highly localized, and short termed. Bottom trawl catches of rock sole about 1 year after the test (August–September 1972) equaled pretest catches. Repopulation was probably by immigration of adjacent rock sole populations into the affected region.

Concurrent with the November 1971 offshore fish-sampling program after Cannikin, nearshore fish sampling with trammel nets focused on rock greenling, which were observed killed in large numbers (277) by Cannikin. Net sets were short (less than 5 hr) during posttest sampling because of weather; thus many of the longer pretest sets could not be compared. The results of the pretest and posttest sampling for rock greenling, including the continuing effort through October 1972, are shown in Fig. 12. The short sets in November showed that there was a marked temporary decline in abundance of rock greenling from about 10 fish per hour to about 4 fish per hour. The two sets made in April 1972 averaged about 7 rock greenling per hour. Repopulation approached pretest

*Uplifts were as great as 1.1 m (3.6 ft) and accelerations as great as 10 g (Merriitt, 1973).

†The data, transformed to the number of individual fishes caught per hour, were corrected to the mean pretest sampling depth [70.5 m (230 ft)] according to a positive relationship between catch (rock sole, Pacific halibut, and total catch) and sampling depth.

Fig. 11—Beaches searched post-Cannikin and locations of dead, injured, and stranded fishes and skeletons of fishes recovered from marine areas post-Cannikin. D+3 is 3 days after Cannikin. A 1000-m UTM grid is shown.

Fig. 12—Trammel net catches of rock greenling per hour, for short (<5 hr) sets in inshore/rock-algae fish community adjacent to intertidal sites IA-2 and IA-3, August 1971 through October 1972. A range is indicated where more than one set was made on a given day.

levels by fall 1972 when catches averaged about 8.5 rock greenling per hour (Fig. 12). As with the offshore rock sole, rock greenling repopulation was most likely by the immigration of rock greenling from nearby unaffected nearshore waters.

Finally, two anomalies were noted in the species composition in trammel net catches in the inshore fish communities before and after Cannikin. In the inshore/rock-algae community, four species (searcher, great sculpin, Pacific halibut, and Alaskan ronquil) were not captured after Cannikin; a few individuals of each of these species had been caught before. In the inshore/sand-gravel community, two species (Atka mackerel and dusky rockfish) were caught before but not after Cannikin. In both cases, considering seasonal differences, differences in the duration of sets, and the infrequent occurrence of these species in the area, the species composition and abundance are comparable (Nakatani and Burgner, 1974).

Summary of Impacts on Marine Fishes

In review, the data available from Cannikin experiments and observations do not permit precise quantification of the impact of that test on marine fish communities. Cannikin had both direct and indirect impacts on marine fishes inhabiting the Bering Sea littoral bench, which was uplifted during the test. These areas have been denied for some time, perhaps forever, as habitat for marine fishes, both those which are resident members of the community and those of adjacent communities which use the bench for feeding at high tide, e.g., the rock greenling. A precise quantitative assessment of fishes actually killed during the uplifting cannot be made with the data available; however, hundreds of dead fish were collected, which implies a significant short-term impact.

The direct impacts observed after Cannikin were not fully expected (Fig. 11). The majority of the dead fishes recovered were found on or near the uplifted Bering Sea littoral bench or along the Pacific Ocean coastline. One trawl in the Bering Sea, 6 km (4 miles) from Cannikin SZ, captured a dead rockfish, a significant datum since we have never before, in over 4 years of trawling about Amchitka, encountered an obviously dead fish in our catches. Comparison between pretest and posttest catches in the Bering Sea off Cannikin SZ showed marked declines in rock sole in offshore otter trawl hauls and rock greenling in inshore trammel net catches. These two species of fish recovered to pretest levels within a year after the test.

From these observations we conclude that Cannikin had a significant short-term prompt

impact on Bering Sea and Pacific Ocean marine fishes within a 6-km (4-mile) radius of the test site. Complete detectable recovery of these populations, probably by immigration from unaffected areas, occurred after 1 year. Because of adverse weather conditions and the tendency for dead fishes to sink, few dead fish (Pacific cod and rockfish species) were recovered after the test, but the implications of our other data are that marine fishes numbering in the order of thousands were killed in the vicinity of Cannikin SZ. Although this may seem a major impact, its significance to the marine ecosystem of Amchitka Island must be considered as minor, especially when there was a documented recovery within a year or less.

The uplifting of a section of the littoral bench and consequent loss of habitat had only a slight indirect impact on inshore marine fishes. The uplifted area no longer available to these fishes is but a small percentage of the total littoral habitat of Amchitka. Again, as with fish kills, this impact was confined to the Cannikin SZ vicinity.

SUMMARY

Research on the marine fishes in the seas around Amchitka Island was conducted over a 7-year period, the primary objective being to evaluate the prompt and long-term impacts of nuclear testing on marine fish populations. Despite the mission-oriented nature of this research, which imposed some restraints on the scope of the investigations, the studies have led to new understandings of the role of the Amchitka marine fish fauna in the structure and functioning of the marine ecosystem surrounding the island. Information collected on the 92 fish species taken from marine waters around Amchitka has significantly expanded knowledge of Aleutian ichthyofauna. Collections demonstrated the presence at Amchitka of several fish species not previously reported beyond the eastern part of the North Pacific. The new information reinforces the concept of an Aleutian "filter bridge," which was suggested earlier by Wilimovsky (1964) and others. The Alaska Stream apparently serves both as the primary dispersal mechanism for pelagic eggs, larvae, and juveniles of indigenous fishes and as a barrier to eastward expansion of western Pacific species. However, this barrier is not an absolute one because we have tentatively identified larvae of typically Asiatic species in collections made off Amchitka. We can only speculate about possible exclusion mechanisms responsible for the occurrence of only larval forms of these species in the vicinity of Amchitka.

The structure of seven fish communities associated with specific epipelagic, midwater, and bottom habitats has been characterized in relatively broad and subjective terms. Recurrent group analysis of the data identified 13 species associations in five of the communities and provided additional understanding of the internal structure of the species groupings, especially with respect to some significant relationships between midwater predator species and their invertebrate prey.

Our sampling methods were not sufficiently precise to detect any statistically significant changes in community composition during the 7-year collection period. However, catch data revealed what appeared to be one population shift of considerable interest, which occurred after an intensive harvesting of Pacific ocean perch near Amchitka by foreign fisheries in the late 1960s. Following this intensive fishing effort, there appeared to have been a reversal of dominance in the demersal Pacific ocean perch—walleye pollock association, with walleye pollock becoming the dominant member of the assemblage.

Our studies indicate that the algae-based detritus component of the inshore marine ecosystem is largely responsible for the structure and energy flow in the food web of that ecosystem. Results of stomach analyses of fishes suggest that the extremely high densities of epipelagic crustaceans that use this food base (amphipods and mysids) support a large standing crop of benthopelagic-feeding fishes, most notably rock greenling and Atka mackerel. The whole question of the stability of this particular food-web structure takes on new dimensions when the role of the top carnivore of the system, the sea otter, in regulating herbivore populations is realized (Palmisano and Estes, Chap. 22, this volume).

As a major prey organism of nearshore fishes, the Pacific sand lance was second only to amphipods in the number of identified food-web links to inshore predators. Although we were unable to evaluate fully the abundance of the Pacific sand lance, we consider that the role of this planktivorous fish in importing biomass from offshore waters into the inshore ecosystem is an important feature of the inshore portion of the marine food web.

The effects of the underground nuclear testing program were very difficult to evaluate, but our efforts in documenting the impact of pressure pulses and shock waves on Amchitka marine fishes have contributed to the limited knowledge of the prompt effects of such perturbations on aquatic organisms. Bottom pressure changes of 300 psi over and 200 psi under ambient pressures in a

shock wave of 10 to 15 Hz coupled with bulk cavitation of the marine waters in a relatively small area adjacent to the Cannikin test site resulted in the death of large numbers of several species of fish in offshore waters. This conclusion was based on an observed posttest decline in catches of rock sole, a fish that theoretically, by its lack of an air bladder, should be little affected by such pressure changes. Populations of more susceptible species, such as Pacific cod and several rockfish species, were assumed to have been affected also, although direct evidence to support this assumption is meager. A year after the test, catches of rock sole equaled pretest catches; reestablishment of the population was probably by immigration from nearby unaffected stocks.

In the littoral environment, catches of rock greenling declined sharply in Bering Sea waters adjacent to the Cannikin site immediately posttest. The decline was attributed to a substantial kill of rock greenling in the area resulting from a combination of forces generated by the Cannikin detonation. Catches posttest indicated that the affected population had begun to recover within 2 weeks after the detonation and had fully recovered by fall of the next year. Recovery was judged to have been by immigration of greenling from stocks outside the affected area.

Although both offshore and inshore fish populations in waters adjacent to the Amchitka test sites were adversely affected by the nuclear detonations, especially by the Cannikin test, the changes were short-term. Within a year after the Cannikin detonation, no effects on fish populations were detectable. Since the total area of marine habitat affected by the tests was such a small fraction of the total habitat around the island, the overall effect of the tests on the Amchitka marine ecosystem should be considered transitory and insignificant.

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Sea Mammals: Resources and Population

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The marine mammal resources near Amchitka Island consist of sea otters, harbor seals, and Steller sea lions as permanent residents, northern fur seals that migrate through Aleutian passes, and whales and porpoises in the surrounding seas. Archaeological and historic data on animal populations indicate that the species present then were the same as those present today and demonstrate the continued importance that sea mammals have played in the island's history. Sea otter observations and surveys made from 1935 to 1974 document the recovery of this species

from near extinction at the start of the twentieth century. Conservation measures, national and international, have been many, some even having been started in Russian times. The crucial and finally successful ones are the Fur Seal Treaty of 1911 and the Executive Order of 1913, which established what is now known as the Aleutian Islands National Wildlife Refuge. The marine mammal populations (whales excluded) around Amchitka and in the western Aleutian Islands are in good condition.

ARCHAEOLOGICAL INDICATIONS OF SEA MAMMALS

The prehistoric people of Amchitka, in common with the historic Aleuts, had a maritime economy and were dependent on the sea for the bulk of their existence. These people also applied their skills in ocean fishing to marine mammal hunting. They were expert seamen and traveled in groups or family units from one island to another without difficulty. The practices required for existence on Amchitka and in the Aleutians in general changed very little during several millennia of human occupation.

From their 1971 dig on Amchitka, Cook, Dixon, and Holmes (1972) report the recovery of numerous sea mammal bones, which were apparently used as awls, casting lance heads, picks, and for decoration. Among these were eight notched or grooved teeth, including four harbor seal canines, one sea lion postcanine tooth, and three harbor seal incisors. Desautels et al. (1970) recovered 25 grooved teeth from Amchitka excavations in 1969. One of these was perforated as well as grooved. Clark (1968, cited in Cook et al., 1972) did not report finding grooved sea mammal teeth on Kodiak; however, Spaulding (1962, cited in Cook et al., 1972) mentioned sea lion teeth that were grooved on one end from Agattu. Cook et al.

suggest that these grooved teeth were used for personal decoration—as pendants for nose ornaments.

Desautels et al. unearthed fireplaces associated with large cut whale bones. The close association suggested to them that these may have been used as supporting beams for structures. None of these bones were found in an upright position.

The animal remains from the six sites dug by Desautels et al. in 1969 consisted of sea mammal, fish, and bird bones as well as shells of marine invertebrates. Site RAT 31 yielded more than 11,000 mammal bones. Except for some human elements, the remainder were from whales, pinnipeds, and sea otters. The few whale bones represented both large and small cetaceans. Species identified included sea otters, harbor seals, Steller sea lions, and a few northern fur seals. About 50% of the sea otter bones were from juveniles. From the material collected, it appears that whole sea otters were brought back to the village sites but pinnipeds were butchered elsewhere. Percentages of sea mammals found in site RAT 31 generally reflect historical records concerning Aleut food preferences. Desautels et al. report Hrdlička (1945) as having said that sea otters, which were available near the shore, were killed in large numbers and that the Aleuts also killed many young harbor seals. These statements are in general agreement with the numbers and species of the animal remains from site RAT 31. Far fewer sea lion bones were found compared with the number of

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sea otter and harbor seal bones. The small number of fur seal remains is consistent with that species being a migrant without established rookeries in the area. Desautels et al. found sea mammal bones and teeth made into harpoon and dart heads, fishhooks, wedges, flakers, awls, clubs, and ornaments.

EARLY HISTORY OF THE FUR TRADE

The history of the Aleutian Islands clearly emphasizes the importance of the sea otter. Elliott (1887, pp. 484-485) wrote:

To the sea otter geographers owe their early knowledge of Russian-America; had it not been for the greed and covetousness excited in the minds of fur dealers by the beauty and costliness of its peltries which Altasov and his Tartars first secured, towards the close of the seventeenth century, on the Kamchatkan coast,—had it not been for this incentive the exciting, pushing, aggressive, indomitable search made by the Russian 'Promishlyneks' would never have been undertaken. Indeed, for that matter, much of the glory which old Titus [sic] Bering is enveloped with, as a discoverer, was not due to his love for geography or hydrography, but it was the direct stimulation of fur hunters for a rich return. They backed him; they fitted out his small, miserable vessels, which in light of the present hour, make his voyages fairly fabulous, when the rickety, 'ram-shackley' construction of his rough Amoor-built shallops is understood . . .

It was not, therefore, until the Russians opened up the trade, swiftly supplemented by the third voyage of Captain Cook and the aroused attention of the Hudson Bay Company, which speedily began to search the coasts of British Columbia and Oregon in those early days—it was not until this action was taken, toward the close of the seventeenth century and the beginning of the eighteenth, that the sea-otter became known, first to the courts and then to the nobility of the civilized world . . .

During the first few years after discovery the numbers of sea-otters taken all along the Aleutian chain, and down along the whole northwest coast as far as the southern boundary of Oregon, were very great, and, compared with what are now captured, seem perfectly fabulous. For instance, we are told when the Pribylov Islands were first discovered, two sailors, Lukannov and Keikov, killed at St. Paul's Island during the first year's occupation, 5,000, but the next year they secured less than 1,000 and six years after not a single sea-otter reappeared, and none have been there since.

When Shelikhov's party first visited Cook's Inlet they secured 3,000; during the second year 2,000; in the third season only 800, and in the succeeding year they obtained 600, and finally, in 1812, less than 100, and since then not one-tenth of that number, although I am told, at the date of this writing, that during the past two years more than 500 sea otters annually have been taken on the coasts of Cook's Inlet . . .

Eighteenth Century explorations throughout the North Pacific area opened up new regions to colonization and exploitation. Sea otters and other

valuable fur-bearing animals served as the catalyst for this exploration. A Russian vessel is reported to have sailed to the Arctic Ocean from Kamchatka through the Bering Strait in 1648. In 1728 an expedition under Vitus Bering sailing northeasterly from Kamchatka discovered St. Lawrence Island and passed through the strait later named for him. Another Russian naval expedition sailed in 1733 but met with misfortune. There are no further accounts of explorations from 1733 to 1741 (Golder, 1914).

A second expedition led by Bering in 1741 made landings along the northwest coast of North America and in the Shumagin Islands. Several of the Aleutian Islands were seen during this voyage. Bering's ship was finally shipwrecked on one of the Commander Islands, and Bering died on the island that now bears his name. The return of his lieutenant, Chirikov, from the same area was of particular importance in turning attention to those shores. Chirikov's crew brought back many valuable furs, including the skins of 900 sea otters. Rumors of the richness of this newly discovered country kindled a spirit of enterprise in the merchants of Siberia. Tales of Bering's companions and crew, when they returned in 1741, did even more to increase the desire of merchants to profit from trade in sea otter skins, and, during the remaining years of the eighteenth century, merchants and adventurers made numerous voyages eastward from Russia.

The first fur hunter to undertake the daring sea voyage in search of sea otters was Emilian Basov, a Cossack sergeant from Kamchatka. He made four voyages but only reached Bering and Copper Islands. Later trips by others led to the discovery of new islands and to surveys of the Alaska mainland.

In 1763 Shelikhov, a prominent Siberian merchant, led an expedition to Bering Island, Unalaska, and Kodiak. He spent 4 years on these islands and established his own trading company, which later formed the nucleus of the Russian-American Company. In 1790 Shelikhov employed Alexander Andreevich Baranof to organize and manage the affairs of his company. Baranof used his talents to develop and increase hunting and trading throughout the Aleutian Islands and mainland Alaska.

Foreign ships also visited these shores. Berkh (1823, translated in Ricks, 1963, p. 38) says that Shelikhov complained in 1787 to Governor Jacobi about foreigners on American shores belonging to Russia:

In August of last year during my sojourn in Petropavlovsk Harbor, I learned from William Peters of the [British East] Indian Company that a ship of their

company had visited our boundaries in Latitude 30° on the Northwestern Coast of America in 1785 for trading purposes. I do not know whether or not they had permission from the Russian government. They themselves stated that they bartered more than 800 sea otters and a considerable number of fur-bearing land animals in a short time. It follows from the above stated facts that the great profits which should belong to the Russian citizen are being usurped by people of other nations who do not own the adjoining land and have no rights in this sea.

In 1799 the Russian-American Company was granted a monopoly on hunting in the Aleutian Islands area. In 1811 the Russians, under Baranof, established themselves on the California coast. Baranof was relieved of his post as manager of the North American colonies in 1818. After that Russia's fortunes in the New World began to decline. Sickness, mismanagement, and competition from the Hudson Bay Company were primary factors in the decreasing income derived from the fur trade.

In 1864 delegates of the Russian government began to negotiate with the United States for the sale of Russia's possessions in North America. Congress approved the treaty, transferring the territory in 1867, and the next year appropriated the \$7,200,000, which was Russia's price for Alaska.

When the Russians reached the Aleutians in the 1740s, practically every island was inhabited. Agattu was reported to have had 31 villages and Unalaska 24, with numerous settlements on other large islands. By 1831 there were only 10 villages on Unalaska. Only 15 of the other islands were inhabited, and the total population is estimated to have been less than 2000.

Aleut villages were on the seacoast; the interiors of the islands were completely unoccupied and seldom visited. No people were more dependent on the sea than the Aleuts. The land provided only a few of their needs—stones for knives and other implements, grass for weaving, and a few plants for food. Everything else came from the sea. For most of their food they depended on sea mammals, fish, sea birds, sea urchins, and mollusks. Their clothing was made from the skins of the sea mammals and birds and their boats from driftwood and skin. Implements, weapons, and household utensils were made of bone or driftwood, and material for their houses was driftwood and whale bones (McCartney, Chap. 5, this volume).

The Aleuts were skillful sea hunters. In their single- or double-hatched bidarkas (light skin boats), they made long coastal voyages and often ventured far from shore in pursuit of sea otters, seals, sea lions, and even whales. Their weapons were light darts and spears cast with a throwing

board. Sea otter hunting was a cooperative activity requiring from 4 to 20 bidarkas, each carrying one or two hunters. The boats would start out in a wide semicircle, keeping 50 to 100 yards apart. The sea otter comes to the surface to breathe at least every 5 min; his head sometimes remains visible only a few seconds. When an otter came up within casting distance of one of the hunters, he would throw his dart. The otter was not likely to be killed outright by the small bone point of the dart, but its movements were impeded by the dart, and it was soon dispatched (Veniaminov, 1840, Vol. II, pp. 342-344).

Whales were hunted in an entirely different manner. Instead of being surrounded, they were killed with poison lances. Hunters approached whales carefully from the rear, cast their spears, and rapidly retreated. The lance head with its poison blade became detached from the shaft and remained in the whale's flesh, causing the whale to die after about 3 days. If the hunter was fortunate, the whale would drift ashore (Veniaminov, 1840, Vol. II, pp. 132-134).

SEA MAMMAL RESOURCES

Sea Otter (*Enhydra lutris*)

The only immediate government action after the cession of Alaska to the United States in 1867 was to establish a contract with the Alaska Commercial Company for the regulated exploitation of fur seals. It was only 17 years later that a local government was established in Alaska, and there was essentially no regulation of fur hunting and trading in the Aleutian Islands. As a result, by the time of the Fur Seal Treaty of 1911, it seemed that the sea otter population had been exterminated and the fur seal population was in danger of extermination. The treaty devotes only 1 section out of 27 to the sea otter; all the rest, including the very title of the treaty, are concerned with fur seals.

The beginnings of contemporary sea otter studies by Americans were informal. There were intermittent almost casual published references to sea otters between the 1911 treaty and 1935; these were primarily notations that a few sea otter skins had been confiscated or surrendered and subsequently sold at public auction.

Surveys. 1935. The persistence of reports of sea otter observations sent to the Bureau of Fisheries ultimately had its effect. Three memoranda in the files of the Anchorage office of the U. S. Fish and Wildlife Service (FWS) are worthy of mention. The first was prepared June 21, 1935, by Lieutenant Howard B. Hutchinson, U. S. Navy,

for the Commander, Aleutian Islands Survey Expedition. Entitled "A Report on the Existence of Sea Otter in the Rat Islands," it says:

1. The Biological Survey of the Department of the Interior [Agriculture] requested the Navy Department in 1932 to have the Alaskan Survey Expedition of that year investigate and verify the existence of the sea otter (*Enhydra lutris*) which was reported to exist in the western islands of the Aleutian group. The animal was not identified in that year by any member of the expedition, either at Attu or Kiska, although the chief of the Attu Natives assured the commander of the expedition that there were a few at Agattu, which would soon be gone because the Japanese came frequently to take them. 2. On May 1933 [1935?] it was determined definitely that the sea otter does exist in the Rat Island group. On that date, the reporting officer [Hutchinson] while ashore on the northwestern end of Amchitka Island at the survey station, BIRD, saw eight (8) adult animals and three (3) of the young or pups moving about in the kelp beds which surround the station. With the aid of good binoculars, two animals were watched at play in the clear water under the sheer bluff of the station. From this favorable point of vantage it was seen that the animals were sea otter and not seals nor sea lion. There is no doubt that the animal in question is a sea otter.

The memorandum continues with numbers of animals seen and finally an estimate that the sea otter population around Amchitka numbers 1000 adults and 500 pups.

The second memorandum was prepared by Ward T. Bower, Chief, Division of Alaska Fisheries, for a Mr. Jackson on Aug. 19, 1935. It told of a recent telegram from the Commander of the Bering Sea Patrol Force of the Coast Guard and gave an estimate of 1000 to 6000 sea otters around Amchitka Island and indicated that they were spreading to other nearby islands. Bower emphasized the necessity of protective measures so that this gain and reestablishment of sea otters could be maintained and expanded. Bower suggested a conference to be attended by representatives of the Coast Guard, the Navy, the Bureau of Biological Survey, and the Coast and Geodetic Survey to meet during the winter to determine the best means of conserving and protecting the Aleutian Islands' sea otter herd and to formulate plans that could be put into effect for the next season.

The third memorandum was prepared by Ward T. Bower and sent to Commissioner Bell of the Bureau of Fisheries. Bower's memorandum says in part:

This morning Captain B. L. Canaga, Room 2058, Navy Department, Telephone Branch 214, called at this office and said that a confidential report had been received from an officer attached to the Navy Expedition to the Aleutian Islands this summer in regard to sea otters in that region. Captain Canaga permitted me to read the report and then took it away with him. He

said it was planned in due course to send a copy to this Bureau for appropriate consideration. As I remember, the report showed that about 600 sea otters were observed at Amchitka Island this summer. Captain Canaga said that another report, a copy of which he also had planned to have sent to this office, referred to about 1,000 sea otters at another place. Captain Canaga expressed apprehension lest Japanese might capture numbers of these valuable animals for their pelts. He suggested need of adequate protective measures. I suggested to Captain Canaga that the Navy Department might be able to cooperate in this work in connection with expeditions to the region. I further suggested that as a feature of such cooperative effort, the Navy Department might consider the establishment of a radio station in the region and thus, in addition to the Bureau of Fisheries employees, there would be the radio station personnel.

1936. O. J. Murie and C. S. Williams were assigned to make an inventory of resources in the Aleutian Islands Wildlife Reservation, as it was then called. This inventory was initiated primarily because of the government's responsibilities relating to the blue fox industry in the Aleutians and not from concern for sea otters. Murie (1959, p. 285) says:

In spite of occasional poaching, in 1936 we found substantial sea otter populations in several places throughout the Aleutian chain, and we made a conservative estimate of 2,000. Most heartening of all, they were extending their range, not only in the Aleutians, but also along the Alaska Peninsula. However on our last visit to Sanak Islands, the sea otters had not reappeared, although at one time this area was one of the best sea otter hunting territories (since our visit, five sea otters have been seen).

The data obtained in 1936 indicated that there were still a few otters remaining about isolated islands, and infrequently they visited bays of the North Pacific. The most southeasterly point at which they were reported was Montague Island in Prince William Sound. To the east, trappers and local residents said sea otters were present near Shuyak Island and Latax Rocks, just north of Afognak Island in the Kodiak group. From Sutwik Island near the lane of Alaskan shipping, they were also reported. Eleven sea otters were seen off Simeonof Island in the Shumagins. The rocky Sanak group was reported to harbor a few, whereas information obtained from Mr. Homer Jewell, Alaskan Game Warden, indicated that they occurred on the Alaskan Gulf side of the Alaskan peninsula at Aiugnak columns, the southeast portion of Cape Kumlik, and at Kujulik Bay.

In the Aleutian Islands proper, natives said that otters occurred occasionally about the following islands: Seguam, Little Tanaga, Kanaga, Kiska, Semichi, Agattu, and Attu. The survey party visited all these islands except Semichi and Agattu but observed no sea otters. However, the party did

encounter the animals at Umak, Ulak, Kavalga, Ogliuga, Amchitka, and Tanaga Islands.

At most of these islands, only a few sea otters were seen, the greatest number at any one island being 48. Nowhere were they abundant, 10 per mile representing the greatest concentration observed. The islands of Amchitka, Ogliuga, and Tanaga appeared to be the most productive; a most liberal estimate of the number of otters occurring about the three being 700. The small concentrations near other islands might raise the total number of sea otters in North America to 2000. To add a note of contrast, in the early 1800s, one island, Unalaska, produced 1000 of the animals annually.

In the 1936 Alaska Fisheries and Fur Seal Industries Report, Bower (1937) noted that five Coast Guard cutters were assigned to patrol the North Pacific Ocean and Bering Sea for the protection of fur seals and sea otters. Lieutenant Commander S. P. Swicegood, U. S. Coast Guard, commanding officer of the *Chelan*, reported a count of 814 sea otters on Amchitka (Swicegood, 1936).

1937. Comments on sea otters this year by Bower (1938) were:

A substation on one of the western Aleutian Islands was established for the expansion of sea otter investigations and patrol. . . . Two trips [by the *Penguin*] were made to the western Aleutians—one in July and one in September—in connection with the sea otter patrol.

In this year Loy and Friden (1937) counted 1321 otters on Amchitka, almost all of them on the Pacific coast.

1938. Substantially more information appeared for this year in the report by Bower (1940, p. 161). A two-paragraph description with the heading "Substation for sea-otter patrol" reads:

The Bureau's work for the furtherance of sea-otter investigations and patrol was continued. At the substation established on Amchitka Island in 1937, 4 additional overnight cabins, 8 X 10 feet, were built on the south side of the Island at 8-mile intervals. At the camp site in Constantine Harbor, a 10 X 16-foot powerhouse was constructed and a 5-horsepower engine was installed for use as a power plant. Two radio masts were erected on concrete bases, and radio antennae were strung leading to a receiving set and a transmitter. Buildings that had been erected in the previous year were given a coat of paint.

The number of sea otters counted in the vicinity of Amchitka Island in 1938 was considerably less than the estimate for the previous year. Whether the difference was due to an error in the count or to a change in the habits and distribution of the animals was not known. It is anticipated that further light will be thrown upon this problem by investigations in succeeding years.

A partial count of sea otters around Amchitka numbered 1321 animals; this was extrapolated to arrive at an estimate of 1761 animals for the entire island.

1939. Reference to the Amchitka sea otter investigation was given coverage again in the 1939 Alaska Fisheries and Fur Seal Industries Report (Bower, 1941, p. 159) with the following statement: "The substation which was established on Amchitka Island in 1937 for sea-otter investigations and patrol, and which had been in operation each summer since that time was maintained on a year-round basis during 1939-40." The sea otter count this year was 1355 animals; the total-population estimate, including pups, was 1870 (Loy, 1940). Lensink (1962) also reports an earlier count that year of 1030.

1940. J. B. Mangan and Grant Ritter, sea otter wardens on Amchitka for the Bureau of Fisheries, estimated the Amchitka sea otter population to be 1650, 69 being pups, from a census made in July and August (U. S. Fish and Wildlife Service, 1940, unpublished report).

1943. The first known account of an aerial survey for sea otters is recorded in a letter dated September 28 from Frank L. Beals, Refuge Manager, Aleutian Islands National Wildlife Refuge, Kodiak, to Frank Dufresne, Regional Director, Fish and Wildlife Service, Juneau (U. S. Fish and Wildlife Service, 1943, unpublished report). Accompanying the letter is an outline chart of Amchitka and Rat Islands; numbers of otters seen are noted on the chart at the point of observation. The sea otter count on June 24 for Amchitka was 3417.

Mr. Beals was very active in the Aleutians before 1942 and made conspicuous efforts to continue this activity during the period of military operations. His letter is reproduced in its entirety:

The following report is made of an attempt to estimate the sea otter population of Amchitka and Rat Islands, Alaska, through the use of aeroplanes.

While engaged in regular patrol of the Aleutian Islands National Wildlife Refuge it became my good fortune to make the acquaintance of a Squadron of U. S. Navy Observation-Scout Pilots, then stationed on Amchitka Island. At their suggestion and with the permission and sanction of the Commander of the U. S. Army Force and the Captain of U. S. Navy Facilities for Amchitka Island I was taken on flights around Amchitka, Rat, Segula, and Little Sitkin Islands for the purpose of observing sea otter and estimating their number and general distribution.

U. S. Navy Pilot G. T. Joynt, a former biology student already actively interested in sea otter, had on previous occasions observed their general location in this area. To Mr. Joynt belongs most of the credit for what success we had in checking their numbers in the

Amchitka—Rat Island area. The other pilots were willing and helpful with their time and personal observations but it was the old biology student who smelled them out and maneuvered his plane in position for effective observation.

The type of plane used was ideally suited for this work as it throttled down to fly safely and with stability at close to one hundred and thirty miles per hour. Good visibility from an open cockpit can be had if desired by simply cranking back the protective cowling and banking slightly when over the object to be observed.

Our method of procedure was to fly around the island a number of times to become familiar with landmarks and principal concentrations. Then over the plane's interphones to communicate our opinions and reach an agreement on each pod of sea otter observed and plot it on an outline chart of the island. An average size pod was selected and its actual number of animals counted as closely and accurately as possible. This was then used as a yardstick in estimating the number of otter in each of the other groups encountered.

The results of our survey are not offered as anything more than an approximation. I believe it was always our tendency to see and estimate more animals than actually were in the groups. Because of the sea otters peculiar and characteristic position in the water, that is of floating on its back with the two extremities of its body prominently displayed, head and forefeet at one end, hind flippers and tail at the other end and its midsection mostly submerged and hidden from view, one is inclined to see two animals where there is really only one and come out on the plus side in the count. Offsetting this somewhat is the fact that we did not count or include singles and pairs in the survey and they represent an appreciable number of otter when the entire island is considered.

The majority of groups observed were in the offshore margin of the kelp fringe that rings the islands. Singles and pairs, etc., were noted to keep closer inshore and often right in the middle of thick masses of kelp. Only rarely were sea otter observed in open water more than two miles from shore or half a mile from protective kelp patches. Mr. Joynt and his friends report that it is rare indeed that they have seen an otter as far as five miles offshore but that they have observed an occasional single animal idling along on its back as far as 10 miles from the nearest land.

I personally experienced difficulty in picking out young sea otter riding on their mothers midsection but Pilot Joynt, whose eyes are more alert and better trained, claims to have seen many of the little fellows. He thought as many as one juvenile to each ten or twelve adults. I would not want to offer an estimate of young sea otter around Amchitka and Rat Islands but judging from personal observations made from shore through high power field glasses, they do not appear to be less than I remember having observed on past visits to Amchitka.

It is interesting to note that the sea otters reaction to aeroplanes is entirely negative. They seem to accept the plane as something natural and quite ordinary. On several occasions we came down on them with engine roaring and approached as close as fifty feet above them. They only twitched their whiskers and went right on with their loafing. One or two of them might submerge but not with any display of great fright or concern. It seems to me that the plane is an ideal tool

for making an accurate check on the distribution and approximate number of sea otter in the Aleutians.

Personal observations from the air were made in the vicinity of Amchitka, Rat, Segula, Little Sitkin, Attu (Massacre and southeastern part only), and Semidi [Semichi] island groups. The only successful flights were at Amchitka and Rat Islands. Poor visibility due to fog plus limited time for choosing good flying weather resulted in nothing of value being learned regarding sea otter about the other islands. Two trips were made from Amchitka to Davidoff and Khvostoff islands but each time fog whipped in and forced a hasty about face and hurried trip home. The planes were equipped with wheels and it was not considered prudent to tempt fate too far.

These same pilots have made many scouting flights around Semisopchnoi Island and report that they have never seen sea otter in that vicinity. Scattered individuals and small groups have been observed in the kelp beds around Davidoff and Khvostoff islands which lie between Segula and Little Sitkin. None of the Observation-Scout pilots at Attu island were familiar with sea otter or know where or how to look for them and say they have not observed the animals as I described them. A civilian boat captain claimed to know what he was talking about and maintains that they are often seen in the kelp off Massacre Bay and around the Semidi [Semichi] Island groups. In an attempt to check up on sea otter in the Semidi [Semichi] groups I encountered difficulty with General Copeland who was in command of the base there and was 'evacuated;' the general does not like civilians, particularly 'D— Game Wardens.' One of the pilots from Amchitka reports having seen 'a thousand or more' in groups of islands around Oglilua and Skagul. A civilian boat captain and several different Army officers told of having seen them in the vicinity of Kagalaska strait and Adak island but I talked with Walt Kamsack, a civilian guide for the Alaska Defense command who has trapped on Adak for the past several years and has patrolled Adak island and adjoining waters for the Army and Navy since its occupation by our armed forces, and in his opinion there are no more otter there than in past years before military activity in the western Aleutians.

1945. A partial count of 365 animals was made from a limited number of checkpoints on Amchitka (U. S. Fish and Wildlife Service, 1953, unpublished report).

1949. Aerial surveys of inshore waters of Amchitka and Rat Islands showed 1321 sea otters around the two islands (Jones, 1951). Lensink (1962) and Kenyon (1969) report that 1087 of these were around Amchitka and the remaining 234 around Rat Island.

1953. The Quarterly Narrative Report for the period September–December 1953, Aleutian Islands National Wildlife Refuge, is quoted (U. S. Fish and Wildlife Service, 1953, unpublished report):

In 1873 (39 [38?] years before the sea otter season was closed in 1911) the Atka Natives took 129 sea otter on their hunting grounds (Buldir Island on the

west to Islands of Four Mts. on the east). The average annual take from 1873 to 1896 was 96 animals. Today, (1953), 82 [80?] years later we salvaged 50 pelts of sea otter from the island of Amchitka alone.

1954. A sea otter survey was conducted by Lensink on April 26 with the following results: "Observations were made from a Navy UF (Albatross) between 1130 and 1500 hours on April 26. Seas were flat, sky partly overcast to clear but visibility was excellent. Transects covered the Delarof Islands, the Andreanof Islands, and Gareloi Island." He reported 320 animals in the Delarof Islands, none at Gareloi, and 684 in the Andreanof Islands for a total of about 1000. "General impressions were that Tanaga and Kanaga have otter populations fully as dense as that of Amchitka. Otter were found on all of the Delarofs, indicating a good population although only one large pod was seen, that being on Amatignak. Characteristics of otter distribution on Amchitka if applied to animals on the Delarofs indicate far more otter are present than were actually counted" (U. S. Fish and Wildlife Service, 1954, unpublished report).

1956. Between May 10 and August 25, Lensink (1962) completed surveys on about half the Amchitka shoreline with binoculars and a telescope. In the first survey 1604 sea otters were counted, and in the second 2568, including 384 pups. Spot-checks on unsurveyed parts of the island indicated that the survey figures could be extrapolated to the entire island, indicating (from the second count) a total population of 5637 animals.

1959. Kenyon and Spencer (1960) made aerial counts of sea otters in the western Aleutian Islands in May and counted 9507 animals. The Amchitka sea otter count on May 19 was 1560.

1962. On March 29 and April 5-10, Kenyon (1969) and others (U. S. Fish and Wildlife Service, 1962, unpublished report) made an aerial survey of sea otters from Kiska Island to Amak Island in the Aleutian Islands, in the Sanak Islands, Sandman Reefs, and Shumagin Islands, and in areas along the south coast of the Alaska peninsula. A total of 10,364 sea otters was observed. Observation conditions were poor in the Rat and Andreanof Islands, but observation conditions east of the Andreanof Islands were generally excellent.

1965. An aerial survey of sea otters from Cold Bay to Attu Island was made during April and May. A total of 12,687 sea otters was counted. The count at Amchitka on May 2 was 1144 (Kenyon, 1969).

1968. From 1968 through 1974, helicopters were used for sea otter surveys on Amchitka Island, and the counts became so numerous that I have summarized them in Table 1.

On Nov. 7, 1967, a small conference was held in Columbus, Ohio, attended by representatives of the Bureau of Sport Fisheries and Wildlife, the Alaska Department of Fish and Game, the Battelle Columbus Laboratories, and the Atomic Energy Commission, to establish acceptable methods of assessing any immediate and long-range effects of underground nuclear tests on the Amchitka sea otter population. One of the conference's four recommendations was to conduct annual aerial surveys of sea otters around the island (Spencer, 1969). Later Spencer determined the following criteria to be "minimally acceptable for helicopter surveys:"

1. Wind velocity less than 15 to 17 knots, preferably westerly.
2. No heavy surf (frequently a residual condition from past storms, even when the present wind velocity is low).
3. Visibility of more than 5 miles.
4. Overcast skies to eliminate sun glare and reflection.
5. Minimum ceiling of 500 ft.
6. No rain.

With the use of these criteria, seven counts were made in August and September. The totals listed in Table 1 are the actual counts of otters seen without any correction for percentage seen. Two surveys were also made at Rat Island, one on September 24 yielded 431 sea otters and one on October 6 yielded 456 sea otters.

1969. A combination of aerial photography and visual observation from a helicopter was used to derive sea otter counts this year. Stephan (1971) reports a maximum count of 2354 otters on September 2. Later studies of the photographic record corrected these results, and the date of the highest survey yielded the three counts listed in Table 1.

1970. Surveys conducted after 1969 returned to visual observations made from a helicopter, following the basic criteria established in 1968. Five full counts and one partial count were made in September, as listed in Table 1 (U. S. Fish and Wildlife Service, 1970, unpublished report).

1971. In this year counts were made of the particular segment of coastline near the proposed Cannikin test; the results of this endeavor are reported by Estes (Chap. 21, this volume). Bad counting conditions allowed only one whole island count to be made, although several attempts were

Table 1—Summary of Amchitka Sea Otter Counts

Date	Method	Count	Observer	Comments
1935	Surface	1500	Hutchinson	Lensink says 1000
1936	Surface	814	Swicegood	Lensink says 804
1937	Surface	1321	Loy and Friden	
1938	Surface	1321	Loy and Friden	Extrapolated to 1761
1939	Surface	1030	Loy and Hewitt	
	Surface	1355	Loy	
1940	Surface	1650	Mangan and Ritter	Estimate
1943 6/24	Airplane	3417	Beals	Lensink says 3420
1945	Surface	365	Gray	Partial count
1949	Airplane	1087	Jones	
1956	Binoculars	1604	Lensink	Extrapolated to 3525
	Binoculars	2568	Lensink	Extrapolated to 5637
1959 5/19	Airplane	1560	Kenyon and Spencer	Extrapolated to 2080
1965 5/2	Airplane	1144	Kenyon and Spencer	Extrapolated to 1520
1968 8/27	Helicopter	2068	Sowl	
	Helicopter	2238	Spencer and Cater	
	Helicopter	1896	Spencer and Cater	
	Helicopter	1863	Spencer and Cater	
	Helicopter	2302	Spencer and Cater	
	Helicopter	1728	Cater	
	Helicopter	1624	Cater	
1969 9/9	Photo+helicopter	2066	Stephan and Mercier	
	Photo+helicopter	2113	Stephan and Mercier	
	Photo+helicopter	2395	Stephan and Mercier	
1970 9/3	Helicopter	1522	Cater	Partial count
	Helicopter	3402	Cater	
	Helicopter	3220	Cater	
	Helicopter	2119	Cater	
	Helicopter	3927	Cater	
	Helicopter	1648	Cater	Extrapolated to 3133
1971 10/2	Helicopter	3241	Cater	
1972 6/5	Helicopter	2564	Abegglen, Estes, and Schneider	
	Helicopter	3931	Abegglen and Estes	
	Helicopter	3524	Abegglen and Estes	
	Helicopter	4042	Abegglen and Estes	
	Helicopter	2230	Abegglen and Estes	
1974 5/26	Helicopter	1545	Abegglen and Schneider	
	Helicopter	3226	Abegglen and Schneider	

made. A survey on October 2 gave a count of 3241 sea otters (U. S. Fish and Wildlife Service, 1971, unpublished report).

1972. Surveys in 1972 were cooperative efforts. Representatives of the Bureau of Sport Fisheries and Wildlife, the University of Arizona Cooperative Wildlife Research Unit, and the Alaska Department of Fish and Game made surveys in May and June, and the former two in August and September. Five counts were made, as listed in Table 1. The September count of 4042 is the largest ever made at Amchitka Island.

1973. No counts were made this year because a helicopter was not available.

1974. During a return task force trip to Amchitka in May of this year, four helicopter surveys were made, two of which yielded whole island counts of sea otters (Kirkwood, 1975).

Population Status. Lensink (1962) and Kenyon (1969) have analyzed the population history of these islands and in particular of Amchitka where most of the population counts were made. Kenyon reports a population increase of about 10% per year up until 1945 and then a population crash to a third of its former peak. Kenyon relied principally on counts from boats and airplanes and concluded that there are now between 1500 and 2500 sea otters on Amchitka, exclusive of dependent young. Estes (Chap. 21, this volume), using more efficient methods of censusing, concludes that there are about 6400 sea otters on the island, but this is not to be construed as a real increase in numbers since Kenyon's work. Kenyon also concluded, as have others before and since, that the population is at the limit the habitat will support; that they migrate from island to island only under conditions of severe crowding; and

that, presumably because of depleted food resources, the Amchitka population consists of smaller animals than in less crowded areas.

Harvests. The best available analysis of the early sea otter productivity is by Lensink (1962), who said:

It is impossible to reconstruct the complete history of maritime trade of the northwest coast and Aleutian Islands, but the records and approximation summarized below indicate that at least 600,000 sea otter skins were marketed during the period of Russian occupation and that the total number of sea otters that were pelted may have exceeded 800,000 animals.

Russian, 1742–1867 (Berkh, 1823; Petroff, 1884)	264,800
Foreign traders, 1785–1798 (Khlebnikov, 1835)	140,000
Americans, 1799–1803 (Sturgis, n.d.)	47,800
Landed in Canton, 1804–1818 (Roquefeuil, 1823)	129,900
Hudson's Bay Company, 1825–1857 (Douglas, n.d.)	5,400
Total	587,900

Bureau of Fisheries reports by Cobb (1906, 1907) and Marsh and Cobb (1908, 1909, 1910, 1911) provide a summary of the number of sea otters harvested in Alaskan waters between 1867 and 1911:

Years	Sea otters harvested
1868–1870	12,208
1871–1880	40,283
1881–1890	47,842
1891–1900	6,467
1901–1910	572
Total	107,372

The Fur Seal Treaty of 1911 caused this harvest to stop, except for poaching, from then until it was abrogated by Japan in 1941. When Alaska became a state in 1959, the statehood act provided that jurisdiction over game and fur-bearing animals, including the sea otter, should pass to the state. Soon state officials decided to harvest sea otter pelts. This phase of management of this resource began in 1962 and lasted until 1970, when it ended for a variety of political and economic reasons. The pelts taken in this harvest were sold at public auction, the first such taking place in Seattle on Jan. 30, 1968. According to Table 2, almost 2600 pelts were taken in these harvests. Additional notes on them follow.

1962. Between January 22 and February 13, 156 sea otters were harvested at Amchitka Island. This was the first sea otter harvest in 51 years and

was conducted by the Alaska Department of Fish and Game with assistance from the U. S. Fish and Wildlife Service. An additional 24 pelts were collected on Amchitka between October 23 and November 3 (K. B. Schneider, Alaska Department of Fish and Game, personal communication).

1963. A harvest of 291 sea otters was made on Amchitka during the period from March 5 to April 12. An additional 20 were killed between July 31 and August 3 (K. B. Schneider, Alaska Department of Fish and Game, personal communication).

1967. The Alaska Department of Fish and Game harvested 300 sea otters at Adak and 205 at Amchitka.

1968. The Alaska Department of Fish and Game harvested 512 sea otters at Adak and Kanaga.

1970. This year the department harvested 955 sea otters in May: 205 from Amchitka, 144 from the Delarof Islands, and 606 from Tanaga.

1971. The Alaska Department of Fish and Game killed 93 sea otters on Amchitka for scientific studies. In Table 2 the "+" for 1971 refers to an unknown number killed by Cannikin.

Transplants. Following World War II, sea otter research continued efforts initiated in the mid-1930s. The natural reestablishment of sea otters in some areas was sufficiently great that concern was expressed by researchers over the carrying capacity of the habitat, particularly around Amchitka. This same concern was later expressed for the Prince William Sound area.

A method considered for reestablishing sea otter populations in areas where they had formerly lived was to physically transport the animals to these sites. One objective of the research program started in 1950 was to determine a suitable method of keeping sea otters in captivity and subsequently a feasible method for their transfer. Jones (1951) and Kenyon (1969) showed that sea otters could be maintained in captivity and could be transported without excessive mortality. Subsequent improvements in these techniques by the Alaska Department of Fish and Game have facilitated transplant activities, and now there is little mortality during actual transplants.

From 1955 until 1972, when the Marine Mammal Act of 1972 stopped the transplants, some 738 animals were moved from their native areas back into areas where they had historically been known to exist and 22 animals were sent to zoos in the United States and Canada (Table 2; the discrepancy between animals shown to be removed

Table 2—Summary of Sea Otter Removals*

Year	Removals from			Transplants to							
	Amchitka	Other Aleutians	Prince William Sound	Attu	Pribilofs	Southeastern Alaska	British Columbia	Washington	Oregon	Zoos	Harvests
1951	35										
1954	22									3	
1955	37				19					2	
1956	26			5						2	
1957	21									2	
1959	39				7						
1960		14									
1962	180										180
1963	311										311
1965	2		41			23				1	
1966			39			30					
1967	210	300								5	505
1968	494	512	2		55	301					512
1969	251					58	29	29		4	
1970	291	750	46				14	30	29		955
1971	188+								63		
1972			58				46			3	

*Sources: Kenyon, 1969; Vanya, 1970; K. B. Schneider, personal communication.

artificially from the population and transplanted or harvested is other loss, in capture or for use in scientific experiments or whatever.) A chronological résumé of some of the details of these transplants to natural-habitat areas and to zoos follows.

1951. An attempt to transplant sea otters this year failed because of lack of basic knowledge about the requirements of the animals. Thirty-five animals that had been captured on Amchitka Island died in captivity before the transplant could take place.

1954. A press release from Headquarters, Seventeenth Naval District, Kodiak, dated May 4 gave the following caption to an accompanying photograph:

The first sea otter to be successfully transported from its native habitat of Amchitka Island in the Aleutians is taken ashore at the U. S. Naval Station, Adak, Alaska on April 20, 1954 from the seagoing tug USS TILLAMOOK. Lt. Francis Bean, USN, of Seattle, Washington, Commanding Officer of the TILLAMOOK, supervises unloading operations as Mr. Robert D. Jones, Jr., Manager, Aleutian Islands National Wildlife Refuge and Expedition Leader, and crew member take the first cage ashore.

This sea otter was one of four captured in March and April on Amchitka and transported to Adak to be held there until the end of May. One of the animals died on May 5. The remaining three sea otters were transported by naval vessel to Seattle to be placed in the Woodland Park Zoo on June 1. They remained there until July, when they were air

shipped to the National Zoological Park, Washington, D. C. All three otters died within a week of arrival.

1955. Sea otters were transplanted from Amchitka to the Pribilof Islands by a chartered fishing vessel, the *Paragon*, between March 28 and April 4. The 19 survivors of the 31 sea otters aboard the ship were released at Otter Island, but Kenyon (1969) is reasonably certain that none survived. Three died within minutes after being placed in seawater.

Two sea otters were transported from Amchitka to Seattle by air and were released in the Woodland Park Zoo on October 10. One died within a few days. The second, a female named Suzy, lived until Oct. 27, 1961.

1956. On April 10 five sea otters captured on Amchitka Island were transported by ship and released on Bird Island in Attu's Massacre Bay by R. D. Jones (U. S. Fish and Wildlife Service, 1956, unpublished report). Jones notes in his report that he knows one of the five otters died after the release.

Two sea otters from Amchitka Island were placed in the Woodland Park Zoo in Seattle July 30 (Kenyon, 1969). One of the otters died 16 days later, after appearing to be in excellent condition on arrival.

1957. An attempt to transplant eight sea otters from Amchitka Island to St. Paul Island was made on December 11; bad weather caused an en route delay, and six otters died that night. A storm

canceled the flight to St. Paul Island, and the two remaining otters were taken to Seattle and placed in the Woodland Park Zoo on December 14. One of the two otters died December 16; the other lived until September 22, 1958 (Kenyon, 1969; Kenyon and Spencer, 1960).

1959. Seven sea otters were transplanted from Amchitka Island to St. Paul Island on May 20. These animals arrived at St. Paul Island in excellent condition after about a 3.5-hr flight from Amchitka (Kenyon and Spencer, 1960).

1965. Kenyon (1969) transplanted one sea otter from Amchitka to the Tacoma, Washington, aquarium in Defiance Park.

An experimental transplant of 23 otters from Prince William Sound to Khaz Bay, Chichagof Island, southeast Alaska, was conducted by the Alaska Department of Fish and Game.

1966. The Alaska Department of Fish and Game transplanted 30 sea otters in September from Prince William Sound to southeast Alaska, 20 to Khaz Bay and 10 to Yakutat Bay.

1968. The Alaska Department of Fish and Game, with cooperation from the Atomic Energy Commission and the Bureau of Sport Fisheries and Wildlife, transplanted 55 otters from Amchitka to St. George Island in the Pribilofs; 301 otters were transplanted from Amchitka to six locations in southeast Alaska.

1969. The Alaska Department of Fish and Game, with cooperation from the Atomic Energy Commission, transplanted 120 otters: 58 to Khaz Bay in southeast Alaska; 29 to Pt. Grenville, Washington; 29 to Vancouver Island, British Columbia; and 4 to the Tacoma aquarium to form a study colony.

1970. The Alaska Department of Fish and Game transplanted 14 sea otters from Prince William Sound to Checleset Bay, Vancouver Island, British Columbia, in July. One of the four taken to Tacoma in 1969 was transferred to the Vancouver, British Columbia, public aquarium. The Alaska Department of Fish and Game and the Atomic Energy Commission cooperated in the transplant of 62 sea otters from Amchitka on July 18–19, 1970: 31 went to the State of Washington (1 died and 30 were released near Lapush) and 31 went to Oregon (2 died shortly after arrival and 29 were released near Port Orford).

1971. The Alaska Department of Fish and Game, the Atomic Energy Commission, and the Oregon Game Commission cooperated in the transplant of 64 sea otters from Amchitka to the Oregon coast. Releases of 40 otters near Simpson

Reef and Cape Arago and 24 otters at Port Orford were made on June 24.

1972. The Alaska Department of Fish and Game, with cooperation from the Fisheries Research Board of Canada and the British Columbia Fish and Wildlife Department, transplanted 46 sea otters from Prince William Sound to Checleset Bay, Vancouver Island, on July 19. In addition, 3 were given to the Vancouver, British Columbia, public aquarium.

Because of its history of near extermination, the sea otter has received more attention from wildlife scientists than any of the sea mammals in the Aleutians. Nevertheless, it has always been noted that large numbers of other sea mammals are also present in the same area. They apparently coexist because they do not compete for the same food supplies. Their numbers and biology are not nearly as well known as those of the sea otter, but the general consensus is that the populations of these other sea mammals are in good condition throughout the western Aleutians.

Northern Fur Seal (*Callorhinus ursinus*)

The Pribilof Islands were discovered in 1786 and 1787 by Gerassim Pribilof, Russian navigator and fur trader. This was the result of more than 18 years of search for the fur seal breeding colonies. Sims (1906) estimated the herd size at the time of discovery to be 2,500,000 animals. Beginning at that time and continuing for the next 150 years, there were periods of extreme exploitation and periods of no exploitation. In 1911, when the United States assumed control of the sealing industry, the herd size was estimated to be 215,000 seals.

The large number of fur seals moving north and south through the passes in the Aleutian Islands and east and west along the chain during migration periods made appearance of the fur seal not unusual.

The importance of the fur seal in the Aleutians is its numbers as a migrant and not as a resident species.

Steller Sea Lion (*Eumetopias jubata*)

This species, named after Georg Wilhelm Steller, was prominent among the sea mammals encountered by the earliest explorers in the Aleutians. The sea lion was also a victim of the ruthless killing of sea mammals by Russians and Americans, and, by the end of the 1800s, relatively few remained. Sea lions were common in the Aleutians, and today they have returned to what has been

estimated as close to their original numbers (Kenyon, 1971).

Scammon (1874) describes the use of sea lions by the Aleuts:

The dead animals are then skinned, and their hides packed in tiers until fermented sufficiently to start the hair, when they are stretched on frames to dry, and eventually to become the covering or planking for the Aleutian baidarkas and baidaras. The fat is taken off and used for fuel, or the oil is rendered to burn in their lamps. The flesh is cut in thin pieces from the carcass, laid in the open air to dry, then tanned, and worked into water-proof clothing. The stomach is emptied of its contents, turned inside out, then inflated and dried for oil bottles, or it is used as a receptacle for the preserved meat; and what remains of the once formidable and curious animal is only a mutilated skeleton.

A systematic use of aerial photography for the evaluation of sea lion populations in Alaska gave Mathisen (1959) data for his count of 149,264 animals. An incomplete count for the Aleutian Islands derived from his data was 73,090 animals. Mathisen pointed out that the counts were of necessity minimum figures because only animals that were on land were counted; animals feeding or away from the rookeries and hauling grounds were not counted. Later analysis by Mathisen and Lopp (1963) increased the Aleutian Islands sea lion population to about 83,000 animals.

Kenyon and Rice (1961) estimated the sea lion population of all Aleutian Islands and areas near the end of the Alaska peninsula to be about 100,000 animals. This figure was derived from the first complete aerial survey of the Aleutian Islands. The estimated number of sea lions for Amchitka was 1250 with the following distribution:

Bird Rock	50
Chitka Point Islet	50
Ivakin Point	300
East Cape	200
St. Makarius Islet	50
Southwest islets and rocks	600

The Aleutian Islands appear to be the center of abundance for sea lions and the point from which seasonal movements occur.

Kenyon's aerial census of sea lions from the Islands of Four Mountains to Sandman Reefs, Mar. 3-4, 1960, was 55,325 animals (U. S. Fish and Wildlife Service, 1960, unpublished report).

1962. A sea lion census was made on March 29 and April 5-10 in connection with the sea otter census. A total of 54,704 animals was counted (U. S. Fish and Wildlife Service, 1962, unpublished report). Robert D. Jones made a census of Steller sea lions at Amchitka by dory. He counted a total of 3584 animals at the hauling

grounds and rookeries on and adjacent to the island (U. S. Fish and Wildlife Service, 1962, unpublished report).

1965. The April 18-May 9 aerial census covering the Aleutian Islands and part of the Alaskan peninsula from Cold Bay to Attu showed a count of 63,933 sea lions. Of this number, 710 were counted at Amchitka (U. S. Fish and Wildlife Service, 1965, unpublished report).

Thorsteinson, Nelson, and Lall (1961) reported on an experimental harvest of sea lions in 1959 to determine the feasibility of a commercial venture. Five sea lion rookeries supplied 616 sea lions; 464 were processed into 200 tons of ground meat and 9 tons of whole liver. There were many technological problems, but the authors determined that sea lions could be taken in sufficient numbers to be profitable.

Private commercial hunters, regulated and monitored by the Alaska Department of Fish and Game, conducted an annual harvest of Steller sea lion pup skins from 1963 through 1972. The total harvest was 45,178 skins, with rookeries in the eastern Aleutians supplying 12,405 of these. None were taken from the western Aleutians.

Harbor Seal (*Phoca vitulina*)

The harbor, or hair, seal occurs throughout the Aleutian Islands, living in protected bays and river mouths and hauling out on small offshore islands and exposed reefs (Kenyon and Scheffer, 1955). Muric (1959) did not find it abundant in the Aleutians during his 1936 expedition, but historical and archaeological evidence indicates that this species was common. It is common today.

Very little research has been carried out on harbor seals exclusively in the Aleutians. Aerial surveys for sea otters have at various times included harbor seals and sea lions as additional species observed, but generally harbor seals have been neglected. The Alaska Department of Fish and Game has had active research and harvest programs in locations other than the Aleutians, and the bulk of seal skins bountied by Alaskan hunters came from more accessible areas.

A harbor seal population is difficult to count because the seals are scattered, breeding in small colonies rather than large rookeries as do fur seals and sea lions. A population estimate for Amchitka Island in 1971 was 900 to 1000 seals (C. Hardy, U. S. Fish and Wildlife Service, personal communication). The results of three harbor seal counts are listed below.

1960. An aerial count of harbor seals from the Islands of Four Mountains to Sandman Reefs,

March 3–4, gave a count of 3591 animals (U. S. Fish and Wildlife Service, 1960, unpublished report).

1962. An aerial count of harbor seals in conjunction with a sea otter census of March 29 and April 5–10 gave a count of 6000 plus animals (U. S. Fish and Wildlife Service, 1962, unpublished report).

1965. An aerial count of harbor seals conducted in conjunction with the April 18–May 9 sea otter survey gave a count of 4868 animals from Cold Bay to Attu Island (U. S. Fish and Wildlife Service, unpublished report, 1965).

Cetaceans

Statistics on how many of different species of cetaceans have been taken annually in recent years in and near the Aleutian Islands are given by Merrell (Chap. 15, this volume). The following species* have been observed or harvested in the area.

Blue Whale (*Balaenoptera musculus*). Blue whales are generally found in three summer locations: (1) the eastern Gulf of Alaska, (2) the area south of the eastern Aleutians, and (3) the area from the western Aleutians to Kamchatka. Doi, Nemoto, and Ohsumi (1967) calculated the summer population of blue whales to be about 1420, a drop of just over 1000 animals from a postwar population of 2430. Rice (1971) interprets these data as an indication that blue whales were never abundant in the eastern North Pacific and that there has been little decrease in their population size. Blue whales have been completely protected beginning with the 1966 season (International Commission on Whaling, 1967).

Finback Whale (*Balaenoptera physalus*). The summer range of finback whales includes the immediate offshore waters of lands around the North Pacific Ocean. The increased pressure of pelagic whaling on this species has reduced this stock to well below the maximum sustainable yield (Ohsumi, Shimadzu, and Doi, 1971).

Sei Whale (*Balaenoptera borealis*). The sei whale distribution in the summertime is similar to that for the finback whale except that sei whales rarely go north of the Aleutian Islands.

Sperm Whale (*Physeter catodon*). The sperm whale is widely distributed and is found north and

south of the Aleutians. It is one of the larger cetaceans and is important to the whaling industry.

Little Piked Whale (*Balaenoptera acutorostrata*). The little piked whale is also known as the minke whale and is distributed widely in the North Pacific.

Baird's Beaked Whale (*Berardius bairdi*). The Baird's beaked whale is distributed throughout the Bering Sea in the North Pacific Ocean. It has been harvested by the Japanese whaling fleet.

Cuvier's Beaked Whale (*Ziphius cavirostris*). The range of the Cuvier's beaked whale includes the waters of the North Pacific Ocean and the Bering Sea. It does not go into the Arctic Ocean.

Stejneger's Beaked Whale (*Mesoplodon stejnegeri*). The Stejneger's beaked whale is found throughout the Aleutians and in the Bering Sea. Its distribution has been correlated with the distribution and migration patterns of Pacific salmon.

Beluga Whale (*Delphinapterus leucas*). Belugas range on both sides of the Bering Strait and down into Bristol Bay on the American side. This species is not known to migrate south of the Aleutian Islands and is only a rare visitor to the Aleutians.

Gray Whale (*Eschrichtius robustus*). The gray whale passes through the Aleutians en route to its summer feeding grounds in the Bering Sea and the Arctic Ocean and again en route to its breeding grounds in the bays and lagoons of Baja California, Mexico. The gray whale is completely protected from commercial whaling efforts.

Humpback Whale (*Megaptera novaeangliae*). Humpback whales are known to occur fairly close to shore in the eastern Aleutians.

Pacific Right Whale (*Balaena glacialis*). Rice (1971) says that the "Kodiak ground," which encompassed the entire Gulf of Alaska from Vancouver Island to the eastern Aleutians, was renowned in the nineteenth century as one of the best areas for hunting right whales during the summer. A few could be found in the southern Bering Sea and all across the North Pacific at that season. This species is protected by the International Whaling Commission.

Bowhead Whale (*Balaena mysticetus*). The bowhead whale is extremely rare in the Aleutians. Bowheads spend the winter in the loose southern edge of pack ice, which usually extends across the central Bering Sea from Kuskokwim Bay to the northern shores of Kamchatka peninsula. This species is protected by the International Whaling Commission.

*The authority for marine mammal nomenclature is Rice and Scheffer (1968). A monograph on the gray whale by Rice and Wolman (1971) revised the nomenclature for this species; the revised version is used here.

Pacific Whitesided Dolphin (*Lagenorhynchus obliquidens*). The Pacific whitesided whale is widely distributed and very common in the North Pacific Ocean.

Killer Whale (*Orcinus orca*). The killer whale is the most widely distributed marine mammal in the world and is commonly seen in the Aleutians.

Pilot Whale (*Globicephala scammoni*). Distribution of the pilot whale is considered to be the northern waters of the Pacific Ocean, including the Aleutian Islands and south to latitude 36° (Nishiwaki, 1967).

Harbor Porpoise (*Phocoena phocoena*). Murie (1959) saw two harbor porpoises on May 23, 1937, in the Shumagin Islands, and, on Aug. 13, 1937, he saw three in the harbor at Atka Island.

Dall Porpoise (*Phocoenoides dalli*). The Dall porpoise is widely distributed in the North Pacific Ocean.

Pacific Walrus (*Odobenus rosmarus*)

The Pacific walrus is associated with the Aleutian Islands because of the proximity of its wintering habitat, the Bristol Bay area. There are records of walruses being killed south of the Alaska peninsula, and Turner (1886, as cited by Murie, 1959) recorded the kill of a 2-year-old male walrus at Attu Island in September 1880. More recently, in 1960 Jones (U. S. Fish and Wildlife Service, 1960, unpublished report) found the intact carcass of a young walrus near South Bight on Amchitka Island. These animals must be regarded as strays; the Aleutian Islands are not a usual part of the walrus range. The rare occurrence of walruses in the Aleutians is reflected in the absence of identifiable walrus midden remains from Aleutian archaeological investigations.

Steller Sea Cow (*Hydrodamalis gigas*)

Murie (1959) says:

Our knowledge of the sea cow depends mainly on the account of Steller, who, in the disastrous winter when Bering's expedition was wrecked on Bering Island after discovery of Alaska in 1741, had ample opportunity to study this animal at first hand. The sea cow furnished food for Bering's party, as well as for other expeditions that used the Commander Islands as a starting point for Alaska. It was exterminated by 1768.*

*Sea cows were very numerous about the coast of Kamtschatka, and the Aleutian islands, at the time when they were first discovered; but the last of this species was killed in 1768 on Bering's island, and none have been ever seen since (Sauer, 1802, p. 181).

There has always been a question whether this animal had ever occupied the Aleutian Islands. Stejneger (1883, p. 84) said Wosnessenski had obtained a rib of a sea cow from Attu Island, and, in conversation, Stejneger expressed the belief that sea cow remains might be found on Agattu Island.

Goode et al. (1884, p. 136) wrote as follows concerning this find: 'Wosnessenski found a rib of the animal on Attu, the last island of the archipelago, but as Brandt suggests, it may have been derived from a *Rhytina* washed thither by the waves. Mr. Lucien Turner kindly informed me that an aged woman stated that *Rhytina* had been seen at Attu by her father, but such testimony is, perhaps, not altogether satisfactory.'

Thus, we may have some evidence that the sea cow may have occurred on the westernmost Aleutian Islands, and it would be extremely interesting to have identification of bones from old Aleut village sites. To date, studies of such midden material have not revealed the presence of sea cow remains, and, on the whole, it is likely that this animal never inhabited these islands except as an accidental straggler.

Recent studies on the archaeology of Amchitka (Desautels et al., 1970; Cook et al., 1972) bear out Murie's statement that midden material has not yet verified the presence of sea cows at those particular locations.

However, a Pleistocene *Hydrodamalis* was discovered on Amchitka in 1969 from interglacial beach sand and gravel (Gard, Lewis, and Whitmore, 1972). The Pleistocene find was identified as *Hydrodamalis* Retzius, 1794. Fragments of the bones and associated pecten shells were submitted for uranium series dating, and this indicated their age to be about 135,000 years.

Berzin, Tikhomirov, and Troinin (1963, cited by Nishiwaki, 1967) reported that six large sea animals were seen by men on the whale catcher *Buran* near Cape [Point] Navarin on the Siberian coast in July 1962. It was presumed that these animals were Steller's sea cows.

Doctors Colin and Kate Bertram (1964), having read the account by Berzin et al., speculated (in English) on the survival of sea cows, citing the survival of fur seals and sea otters as evidence of this possibility, as well as the remoteness and rarely visited nature of the Point Navarin area. However, the very identification of these animals as sea cows has been questioned by Hepter (1965).

CONSERVATION MEASURES

The earliest exploitation of Alaskan fur bearers by the Russians and by poaching Americans and Englishmen can only be described as ruthless and ignorant. Even today the early opinion occasionally crops up that the animals were disappearing, not because they were being overhunted, but because they were moving away to avoid hunting

pressures (Fedorova, 1973, p. 105). Yet, when the Russian government finally interested itself in these faraway territories, it was partly on the basis of regulating and even conserving the fur resources. Thus the Russian-American Company was formed in 1799 by a forced merger of existing companies and given a monopoly to eliminate competition and consequent wastefulness as well as to increase the imperial revenues and to make contact with the natives more humane. In 1805, Rezanov, a nobleman from the court, made a personal inspection trip to Russian America and, among other things, put a stop to the indiscriminate killing of fur seals (Bancroft, 1886, p. 446). In 1833, Governor Muraviev established seasons and quotas and areas where hunting was forbidden (Bergsland, 1959, p. 75; Fedorova, 1973, p. 189).

The purchase of Alaska by the United States in 1867 was in some respects a setback. Congress did concern itself with the fur seal population by acts of 1868 and 1870, under which a monopoly on taking fur seals at the Pribilof Islands was leased to the Alaska Commercial Company. There was no control over the taking of any other fur-bearing animal. Even the number of fur seals continued to decline. It was the actions of 1911 that turned the tide: total protection for the sea otter, a ban on pelagic sealing, and a closely regulated harvest of the fur seals by the government itself. To this has been added recently the State of Alaska's action in transplanting sea otters back into portions of their former range where they had disappeared. These measures have been outstandingly successful. Both populations, fur seals and sea otters, are healthy and viable by any standard.

This section lists the succession of pertinent federal laws and orders relating to the conservation, protection, and management of sea mammals in the Aleutian area. Also included are treaties and international agreements to which the United States is a party. These statutes and agreements are the basis for the status of marine mammals in the Aleutian Islands today.

Acts of 1868 and 1879 applying to the harvest of fur seals in the Pribilof Islands.

A treaty between the United States and Great Britain (acting for Canada) was concluded on Feb. 29, 1892, at Washington, D. C., for the purpose of submitting to arbitration certain questions concerning the preservation of fur seals.

On Feb. 21, 1892, the 52nd Congress acted to extend to the North Pacific Ocean the provisions of earlier statutes protecting fur seals and other fur-bearing animals.

The Tribunal of Arbitration at Paris made certain awards, and the 53rd Congress acted on Apr. 6, 1894, to give effect to these awards. Congress, on Dec. 29, 1897, acted to prohibit the killing of fur seals in the waters of the North Pacific Ocean.

The Act of Apr. 21, 1910, prohibited the killing of sea otters or fur seals within the limits of Alaska or in the waters of Alaska.

On July 7, 1911, the governments of the United States, Great Britain (on behalf of Canada), Japan, and Russia signed a Convention for the Preservation and Protection of Fur Seals (and sea otter) (37 Stat. 1542, Treaty Series 564). This convention, commonly known as the Fur Seal Treaty of 1911, prohibited pelagic sealing and sea otter killing in high seas waters north of the 30th parallel of north latitude. It also prohibited the importation of sea otter skins into the four treaty member countries unless the skins had been authenticated as to legality of origin. The treaty was terminated when Japan abrogated it on Oct. 23, 1940, effective Oct. 23, 1941.

The existence of the Aleutian Islands National Wildlife Refuge stems from Executive Order 1733, dated Mar. 3, 1913. Its full text is given in Appendix A of Chap. 6 of this volume.

A Convention for the Regulation of Whaling was concluded at Geneva on Sept. 24, 1931, and came into force on June 17, 1932. The convention and the international agreements following it are the basis for the present International Convention for the Regulation of Whaling. In making this agreement, the various world governments signing it proclaimed that they recognized the interests of nations of the world in safeguarding for future generations the great natural resources represented by the whale stocks. They recognized that the history of whaling had been one of fishing one area after another and of one species after another to such a degree that it had become necessary to protect all species of whales from further overfishing.

They further recognized that the whale stocks were capable of natural increases if whaling was properly regulated. Increases in the size of whale stocks would permit increases in the number of whales that could be captured without endangering these natural resources. Realizing that it was in the common interest to achieve the optimum level of whale stocks as rapidly as possible by con-

fining whaling operations to those species which were best able to sustain exploitation, a system of international regulations for whale fisheries was established to ensure effective conservation and development. The International Convention with Schedule of Whaling Regulations, signed at Washington on Dec. 2, 1946, entered into force for the United States on Nov. 10, 1948. A 1956 protocol extended the application of the convention to helicopters and other aircraft and included provisions for inspection. The protocol entered into force on May 4, 1959.

The International Whaling Convention is not generally believed to be as successful as its high principles would indicate, but this is too sensitive a matter of current history to go into here.

The lengthy history of the International Whaling Convention is being repeated by the 1954 International Convention for the Prevention of Pollution of the Sea by Oil. This convention entered into force for the United States on Dec. 8, 1961, and sets forth measures to prevent pollution of the sea by oil discharged from ships. A resolution on marine pollution adopted on Oct. 21, 1969, by the United Nations General Assembly acknowledged a significant contribution by oil to pollution of the sea. It noted also effects that might arise from the exploration and exploitation of resources of the sea bed and ocean floor. For that and other reasons, the Assembly convened in 1973 an international conference on marine pollution for the purpose of preparing a suitable international agreement for placing restraints on the contamination of the sea, land, and air by ships, vessels, and other equipment operating in the marine environment.

The Fish and Wildlife Act of 1956 (16 USC 742a-754) established a comprehensive national fish and wildlife policy. It established the present U. S. Fish and Wildlife Service and directed the Secretary of the Interior to provide continuing research, extension, and information services and to take any necessary steps to develop, manage, and conserve fishery and wildlife resources.

In 1957, Canada, Japan, Russia, and the United States executed an interim convention on conservation of North Pacific fur seals. This convention was amended by protocol on Oct. 8, 1963.

The Alaska Statehood Act of July 7, 1958 (48 USC Chap. 2—Alaska, Sec. 6; P.L. 85-508) authorized the transfer of administration and

management of the fisheries and wildlife of Alaska to the State of Alaska. It also authorized the transfer to the state of real and personal property of the United States which is in Alaska and specifically used for the conservation and protection of the fisheries and wildlife of Alaska.

Executive Order 10857 terminated federal functions in Alaska and transferred property held by the United States to the State of Alaska.

The Fur Seal Act of 1966 (16 USC 1151-1187; P.L. 89-702) repeals the Fur Seal Act of 1944. It continues the responsibility of the Secretary of the Interior for conservation and harvesting of North Pacific fur seals and for administration of the Pribilof Islands reservation for various purposes, including conservation of fur seals and other wildlife. It contains provisions specifically protecting sea otters. It authorizes contracts for research on fur seals and sea otters with persons and agencies and provides for payment to the State of Alaska pursuant to the Alaska Statehood Act of 70% of the net proceeds from the sales of fur seal skins taken in harvest programs. It also provides for payments to Alaska of 70% of the net proceeds from sea otters taken by the Secretary on the high seas or within the Aleutian Islands National Wildlife Refuge.

The Endangered Species Conservation Act of 1969 (P.L. 91-135) provided broad authority and policy guidance for a comprehensive program for the conservation, restoration, and propagation of native fish and wildlife threatened with extinction. The Endangered Species Act of 1973 has replaced it.

In establishing the Marine Mammal Protection Act of 1972 (16 USC 1371-1384, 1401-1407; P.L. 92-522), Congress found that certain species and population stocks of marine mammals are or may be in danger of extinction or depletion as a result of man's activities. These should not be permitted to diminish beyond the point at which they cease to be a significant functioning element in the ecosystems of which they are a part and should not be permitted to diminish below their optimum sustainable population. Further measures should be taken to replenish any species or population stock that has already diminished below that population. In particular, efforts should be made to protect the rookeries, mating grounds, and areas of similar significance of each species of

marine mammal from the adverse effects of man's actions.

Beginning on Dec. 21, 1972, there was an indefinite complete ban on the taking of marine mammals and on the importation into the United States of marine mammals and marine mammal products. The Act allows the Secretary of the Interior to issue permits for scientific research and public displays. It also allows the taking of marine mammals by Alaskan Indians, Aleuts, and Eskimos for subsistence purposes or for creating and selling authentic native articles and clothing when not accomplished in a wasteful manner. The Act has jurisdiction over walruses, sea otters, polar bears, manatees, seals, whales, sea lions, and porpoises.

The Endangered Species Act of 1973 (16 USC 1531-1543; P.L. 93-205) extends the principle of protection of endangered species to plants as well as to fish and wildlife. A new category of threatened species has been established. The definition of fish and wildlife is broadened to include any mammal, fish, bird, amphibian, reptile, mollusk, crustacean, arthropod, or other invertebrate. The Secretary of the Interior has been directed to establish a list of endangered and threatened species and to establish regulations for the protection of these species. This legislation also provides for cooperation with and assistance to the individual states and foreign governments. Except for certain limited purposes and under regulations, the importation or exportation of endangered or threatened fish and wildlife is prohibited.

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Population Estimates and Feeding Behavior of Sea Otters

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Feeding behavior and the abundance of sea otters were studied at Amchitka Island, Alaska, between November 1970 and September 1972. Observations of feeding sea otters suggest no differences between sexes with regard to the amount of time spent diving or on the surface. Apparently, diving and surface times both increase in deeper water, but the percentages of time spent on the surface and submerged remain approximately constant throughout the day. No differences in either the pattern or the percentage of time spent feeding, resting, or grooming were observed between summer and winter.

Shore-based counts of sea otters are consistently higher than aerial counts from helicopters. This probably is attributable primarily to the increased amount of time that can be spent viewing an area from shore-based stations and thus the detection of animals that otherwise would have

been submerged and consequently not counted as the aircraft passed overhead. In 1972 the Amchitka Island sea otter population was estimated at about 6400 animals, approximately 40% of which were in the Bering Sea and 60% of which were in the Pacific Ocean. This distribution corresponds with the distribution of sea otter feeding habitat. Assuming that sea otters live within the 30-fathom (55-m) depth contour, I estimate an island-wide sea otter density of 59 animals per square nautical mile of habitat (17 per square kilometer). This estimate may be separated into 68 animals per square mile (20 per square kilometer) in the Bering Sea and 54 animals per square mile (16 per square kilometer) in the Pacific Ocean. I believe that several earlier estimates of the number of sea otters at Amchitka Island were biased low.

The sea otter (*Enhydra lutris*) evolved as an integral part of the near-shore ecosystem in the North Pacific Ocean. During the 150 years from the mid-1700s to the beginning of the twentieth century, this species was driven to the verge of extinction by white fur traders. Exploitation of sea otter populations continued until 1911, at which time the animals were protected by an international convention between the United States, Russia, Japan, and Great Britain. Happily, a few remnant populations survived in the remote Aleutian Islands and along the rugged coast of central California. Presently, populations are increasing, and the sea otter has become reestablished over about one-third to one-half its original range (Kenyon, 1969).

The first extensive account of the sea otter, by Barabash-Nikiforov, was published in 1947. In 1969 a monograph on the sea otter by Kenyon was

published which set forth the results of his own research, which spanned more than a decade, and brought up to date virtually everything known about the species. Subsequently it has been the most germane reference for several investigations, including studies sponsored by the U. S. Atomic Energy Commission on the sea otter population at Amchitka Island.

Kenyon (1969) considered the population status and dispersal trends of sea otters throughout their range as habitat was reoccupied. Subsequently the abundance of sea otters has been estimated several times at Amchitka Island. These efforts have produced a confusing array of results and probably some invalid suggestions of current population trends.

Distribution, female reproduction, and metabolic physiology of the sea otter are becoming more thoroughly understood. Conversely, little is known about reproduction in the male sea otter. Age and sex specific mortality, age class distribution, and a myriad of other aspects of sea otter population biology are either poorly understood or completely unknown.

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This chapter considers population numbers and feeding behavior of sea otters at Amchitka Island. I assume that the population is fluctuating through time about some point of stable equilibrium. This assumption is supported primarily by conclusions made by Kenyon (1969) and is confirmed by my own observations on natural mortality (Estes and Smith, 1973). I also assume that competition for food is limiting further population growth. The amount of time budgeted by the population for foraging activity should reflect this limitation.

MATERIALS AND METHODS

Feeding Behavior of Sea Otters

I observed feeding and diving behavior of sea otters from November 1970 until September 1972. Most of this work was done during January and February 1971 and during July and August 1972. During early phases of the study, I randomly selected observation areas in some of the more remote coastal regions of Amchitka Island. Inclement weather and logistic difficulties soon proved this method of selection impractical and forced the use of only those areas which were easily accessible by road. For this reason Kirilof Point and Constantine Point were most frequently used during later phases of the study. Large numbers of sea otters were always present and observable at these areas. Most of my observations were made along the Bering Sea coast of Amchitka Island because viewing conditions were generally superior there as compared to coastal areas of the Pacific Ocean.

The primary objectives of behavioral studies were to determine (1) the amount of time feeding sea otters spend submerged, (2) the diurnal pattern of feeding and other activity, and (3) seasonal variation in population feeding behavior.

I recorded diving and surface times of feeding sea otters. When possible, the following information also was noted during each observation:

1. The sex and age of the animal (i.e., male, female, and female with pup). Sex was determined by the presence of a penis or teats.* All animals were classified as either adults or pups.

2. The approximate water depth in which the animal was feeding. Water depth was estimated

from the approximate position of the animal as plotted on a depth contour map.

3. Food items captured.

4. Weather conditions.

The minimum sample size for estimating diving and surface times per individual was determined by incorporating the sample variance among diving times (s^2), obtained from a pilot study, and the desired confidence interval of mean diving times (2b) into the formula: $n = s^2 t^2 / b^2$, where $t = t_{\alpha/2, \nu}$ (α is 0.05 and ν is degrees of freedom determined by the sample size of the pilot study).

From this formula (Steel and Torrie, 1960) I determined the number of observations (n) required for a particular confidence interval (2b) at the 0.05 level of statistical significance. Preliminary estimates of mean diving and surface times were gathered from two feeding sea otters. The means and variances of diving and surface times recorded for these two animals are shown below:

	Diving		Surface	
	$\bar{X}$, sec	s^2	$\bar{X}$, sec	s^2
Sea otter No. 1 (female with large pup)	36	106	40	44
Sea otter No. 2 (lone female)	22	91	19	10

Because of the nonhomogeneous sample variance between the diving times of the two animals, the larger sample variance (i.e., 106) was used to calculate n . I arbitrarily defined the desired confidence interval at ± 10 sec, and thus $n = 4.8$. A minimum of five observations of diving and surface times were taken from each animal; more observations were taken when possible. Between observations food items were identified with binoculars or a spotting scope. Food items were simply classified as fish or invertebrate unless they could be more specifically identified.

Diurnal patterns in the feeding behavior of sea otters also were estimated from the same study areas at Amchitka Island. I originally attempted to observe continuously a single individual animal through long periods of time. This technique was impractical and was soon abandoned. I subsequently noted the activity of all sea otters within the viewing range of 10x binoculars at one-half hour intervals and during daylight hours. Sea otter activity was divided into the following categories: (1) feeding, (2) grooming, and (3) resting. Following some experience sea otter activity could be categorized after only several seconds of observa-

*Sex determination of sea otters in the field was more difficult than I had originally suspected. After examining several subadult males that were held in captivity, I concluded that definite sex determination of anything but adults at close range is not possible. Even at short ranges sexually identifying characteristics of subadult animals are often not apparent (i.e., the male's penis or the female's teats). Adult females with pups are obvious at long ranges.

tion of a single animal. Animals whose behavior could not be classified or whose behavior did not fall into one of the above categories were not tabulated. Most of the sea otters I observed could be classified easily into one of the three behavioral categories.

The following criteria were used to categorize feeding sea otters:

1. Possession of a food item.
2. The exhibition of a characteristic chewing movement in which the head moves sharply up and down.
3. Rolling in the water to wash accumulated food scraps from the fur.
4. The close accompaniment of gulls in search of discarded food scraps.
5. Repeated diving.

Sea otters vigorously cleaning their fur were categorized as grooming. Often this involved repeated rolling or violent splashing in an apparent attempt to force air into the pelage. At long distances grooming behavior occasionally may be mistaken for feeding.

Resting sea otters lie motionless on their backs in the water or "haul out" on land.* Frequently resting animals congregate into large closely associated groups, although solitary resting individuals are not uncommon.

I observed sea otter activity during the summer (July and August) and winter (January and February) seasons. The number of observations and the total number of animals observed during each time period, in summer and winter, are shown in Fig. 1.

Techniques for Estimating the Abundance of Sea Otters

Sea otters were counted from shore-based stations with 10x binoculars and a 15 to 60x variable-powered spotting scope and from air by observers who were seated in an Alouette II helicopter. The boundaries of shore-based counting areas are given in Fig. 2. Two study areas each were selected on the Pacific Ocean and Bering Sea sides of Amchitka Island (labeled A through D in Fig. 2). Area A is located adjacent to the Cannikin site along the Bering Sea coast.† Area B was selected with prior knowledge of the sea otter population structure (Kenyon, 1969; personal observation) and the belief that it contained relatively

Fig. 1—Numbers of behavioral observations and total numbers of animals observed. Bar length indicates the number of days for which observations were made at a particular time and season. Numbers at end of bars indicate the total number of animals observed.

large numbers of sea otters as compared to other areas around Amchitka, Areas C and D were selected without prior knowledge of either the population structures or the relative abundances of animals that occupied the areas. Within each study area a number of shore-based viewing stations were selected from which animals could be counted with binoculars and spotting scopes. The helicopter transported observers to these viewing stations. Immediately preceding or following a shore-based count in a given area, sea otters were counted from the air. Aerial counts originally were made by a single observer who was seated beside the pilot. However, later efforts showed that two observers counting animals on either side of a line bisecting the longitudinal axis of the aircraft provided higher numbers, and this technique was subsequently used. Aerial counts with two observers were also made for the entire island.

Animals were counted from shore at each viewing station within a given study area. When people and equipment were available, counters began at either end of the study area and worked toward the center. After several visits to each study area, observers became familiar with confines of viewing stations and were able to avoid overlapping

*"Hauled out" is commonly used to describe marine mammals resting out of the water.

†Cannikin is the code name of an underground nuclear detonation by the U. S. Atomic Energy Commission in 1971.

Fig. 2—Map of Amchitka Island showing the location of shore-based counting areas.

counts of contiguous stations. All observable sea otters were counted by scanning the viewing stations from border to border. Some diving animals as well as others in obscure locations on the surface inevitably were missed. However, virtually no animals were counted twice during a scan of the viewing station. At viewing station boundaries, errors were introduced either by counting one animal twice or by not including it in either station. I believe that the mean of these errors tends toward zero because of the large number of observations and the effort that was made to count only those animals within the prescribed boundaries. Kelp beds or offshore rocks were used as markers or reference points between viewing stations.

We made aerial counts around the entire coast of Amchitka Island or along large coastal segments of the island between June 1971 and September 1972. A number of people assisted with these operations, depending on availability. An additional person recorded the number of sea otters observed in 45 segments into which the Amchitka coastline was divided during all island-wide counts (Fig. 3).

The helicopter was flown counterclockwise around Amchitka at an altitude of approximately 150 ft (45 m) and sufficiently close to shore that the near-shore observer could easily see animals onshore. The helicopter pilot was located at the

right front of the aircraft. Observers were located at the left-front and right-rear seats, and the recorder sat in the left-rear seat. A zigzag pattern was flown through kelp beds or shallow areas extending far offshore. The same pilot was used throughout the aerial counting operation, and flight patterns remained relatively constant after the first several counts. We frequently flew several miles offshore at the east and west ends of Amchitka and at several other places on the Pacific Ocean coast because these areas are shallower than those along the Bering Sea coast.

A subjective classification of sea state and weather conditions was assigned at the beginning of each counting operation. These conditions frequently changed slightly during the census or between areas around the island.

Viewing classification	Description of conditions
1	Ocean surface glassy. Air clear. Sea otters can be seen at maximum range of 10x binoculars. Viewing conditions excellent.
2	Wind velocity 5 to 10 knots (2.6 to 5.1 m/sec). Light ruffle on ocean surface. Sea calm. Sea otters far offshore may not be seen.
3	Water choppy. White caps present.
4	Heavy seas.

Fig. 3—Amchitka Island showing the shoreline segments used in island-wide aerial surveys.

Aerial counts were made only when the viewing classification was 1 or 2. Reliable shore-based counts could only be made when viewing conditions were nearly perfect (i.e., classification 1). Viewing classifications 3 and 4 are equally inadequate for both shore-based and aerial counting.

RESULTS

Feeding Behavior

The diving and surface times of feeding sea otters at Amchitka Island are summarized in Table 1. The sex of the animals, the approximate depth of water in which they were feeding, and the food items they were eating are also included.

No differences between sexes in either diving or surface times of feeding sea otters are apparent from these data. Female sea otters averaged 50 sec per dive and 43 sec per surface period. Males averaged 50 sec per dive and 41 sec per surface period.

Feeding in deeper water apparently causes an increase of both diving and surface time intervals, although this conclusion must remain tentative because of the small amount of data from animals feeding in deep water. The mean diving and surface

times of sea otters feeding in water estimated to be 0 to 5 fathoms (0 to 9 m) in depth were 47 and 41 sec, respectively. The mean diving and surface times of sea otters feeding in water estimated to be between 5 and 15 fathoms (9 to 27 m) in depth were 83 and 84 sec, respectively. Feeding sea otters spend 52% of the time submerged and 48% of the time on the surface.

I attempted to obtain diving and surface times from sea otters feeding in water deeper than 15 fathoms (27 m). Unfortunately the animals took alarm before I could get close enough to obtain any data. Therefore most of my observations on feeding sea otters are from areas less than 5 fathoms (9 m) in depth and where they could be watched from shore.

The available data are insufficient to indicate differences in diving behavior between sea otters feeding on fish or invertebrates. Fish is an important sea otter food item in some areas (Lensink, 1962; Kenyon, 1969; Burgner and Nakatani, 1972). My observations of feeding sea otters indicate that fish are taken opportunistically and that individuals cannot be classified exclusively as either fish or invertebrate feeders.

Diurnal patterns in the activity of sea otters are summarized in Fig. 4. No differences in feeding,

Table 1—Mean Diving and Surface Times, Estimated Water Depth, and Forage Items of 25 Sea Otters Observed Feeding at Amchitka Island

Status of animal	Mean diving time, sec	Mean surface time, sec	Water depth, fathoms	Forage items
Female	42	19	0 to 5	Unknown
Female	44	19	0 to 5	Unknown
Female	43	17	0 to 5	Unknown
Female	37	18	0 to 5	Unknown
Female	47	36	0 to 5	Unknown
Female	38	34	0 to 5	Unknown
Female	48		0 to 5	Unknown
Female	43	31	0 to 5	Invertebrates
Female	55		0 to 5	Fish and invertebrates
Female	79		0 to 5	Fish
Female	44	94	0 to 5	Invertebrates
Female	50	56	0 to 5	Invertebrates
Male	50	25	0 to 5	Invertebrates
Male	38	37	0 to 5	Invertebrates
Male	38	43	0 to 5	Invertebrates
Male	74	60	5 to 15	Invertebrates
Female with pup	36	22	0 to 5	Unknown
Female with pup	90	85	5 to 15	Invertebrates
Female with pup	57	82	0 to 5	Invertebrates
Female with pup	47	39	0 to 5	Invertebrates
Unknown	84		0 to 5	Unknown
Unknown	31	27	0 to 5	Invertebrates
Unknown	47	43	0 to 5	Invertebrates
Unknown	52	71	0 to 5	Invertebrates
Unknown	40	39	0 to 5	Invertebrates
Unknown	86	108	5 to 15	Unknown
$\bar{x}$ Female	50 $\pm$ 4* n = 16	43 $\pm$ 8 n = 13		
$\bar{x}$ Male	50 $\pm$ 9 n = 4	41 $\pm$ 18 n = 4		
$\bar{x}$ 0 to 5 fathoms	47 $\pm$ 3 n = 23	41 $\pm$ 5 n = 19		
$\bar{x}$ 5 to 15 fathoms	83 $\pm$ 5 n = 3	84 $\pm$ 14 n = 3		
$\bar{x}$ Total	52 $\pm$ 3 n = 26	48 $\pm$ 6 n = 22		

* $\bar{x} \pm s_{\bar{x}}$.

resting, or grooming behavior are evident between summer and winter. These seasons represent extremes in daylight and weather. Therefore diurnal patterns in sea otter activity probably are relatively constant throughout the year, at least regarding the amounts of time budgeted for feeding, grooming, and resting.

Two peaks in feeding activity, with concurrent declines in resting activity, are evident during summer days. A peak in feeding occurs about 8:00 a.m. and another peak occurs about 5:30 p.m. Bering Standard Time (subtract 1 hr for local sun time). During winter it is dark at these times. However, a decline in feeding activity from the morning peak is apparent. Diurnal patterns of resting activity of sea otters are inversely related to patterns of feeding activity. The highest percentages of resting animals were during early morning and late evening. An extended peak in resting activity also occurs between about 9:30 a.m. and

3:30 p.m. Grooming activity remains relatively constant throughout the day during both winter and summer.

My observations on feeding sea otters indicate that about 52% of their time is spent submerged. This information, in conjunction with the diurnal feeding pattern, can be used to calculate the expected percentage of the population that is submerged during daylight hours. Let a_i equal the percentage of the population feeding at time t_i . Grooming and resting sea otters spend 100% of the time on the surface and therefore need not be considered. Thus $0.52a_i$ gives an estimate of the percentage of the sea otter population (excluding small pups) that is submerged at time t_i .

The expected percentage of the population that is submerged as a function of time of day is shown in Fig. 5. The increased percentage of the population that is submerged during morning and evening compared with the middle of the day

Fig. 4.—Diurnal and seasonal patterns in feeding, grooming, and resting activity of sea otters at Amchitka Island.

corresponds with increased feeding activity. Diurnal patterns during summer and winter are generally consistent, and the percentages of the population that are submerged are nearly equal during both seasons.

Kenyon (1969) presented data collected at Amchitka Island which indicate that during the month of August sea otters spend 55% of the time feeding. My data are in general agreement, although they show a somewhat higher percentage of time spent feeding. Of 1758 sea otters that I

observed during the winter of 1971, 1095 (or about 62%) were feeding. Sixty-five percent (1910) of 2918 sea otters observed during the summer of 1972 were feeding.

The sea otter population at Attu Island was observed during a 1-day visit to Chichagof Harbor on June 22, 1972. This population probably contained fewer than 100 animals (Kenyon, 1969; personal observation). Several sea otters observed at Attu were feeding on mussels (*Modiolus* sp.), false jingle shells (*Pododesmus* sp.), and sea urchins

Fig. 5.—Diurnal and seasonal patterns of the estimated percentage of sea otters that are submerged at Amchitka Island.

(*Strongylocentrotus polyacanthus*). One sea otter was observed pounding two mussels together on its chest. This behavior also is common to sea otters off the coast of California and is used to break open food items with exoskeletons that are too thick for the animals to open with their teeth. Sea otters at Amchitka rarely pound food, apparently because few large invertebrates are available owing to intense food use there.

I observed no sexual segregation in the sea otter population at Attu. This contrasts with the situation at Amchitka where sexual segregation is well defined.

Estimates of Sea Otter Abundance

The results of island-wide aerial sea otter counts are shown in Table 2. The results of simultaneous shore-based and aerial sea otter counts which were obtained from the study areas shown in Fig. 2 are given in Table 3.

I estimated the number of sea otters at Amchitka by considering simultaneously obtained shore-based and aerial counts and island-wide aerial counts. I assume that shore-based counts accurately represent the abundance of sea otters within localized study areas.

A least-squares technique was used to estimate the sea otter population number (Y_0) at Amchitka Island because, if certain assumptions are satisfied, it provides an unbiased estimate of the parameter (vector). Two linear models for regressing shore-based counts from aerial counts were investigated. Strictly speaking, shore-based counts (Y_i) and aerial counts (X_i), respectively, are random variables representing the i th simultaneous observation. A technique for analyzing linear models when X and Y both are random (Acton, 1959) is based on the estimation of any two of the following

parameters [$\text{Var}(X)$; $\text{Var}(Y)$; $\text{Cov}(X,Y)$], which in turn is possible only when repetitive observations of X_i and Y_i are available at some assumed fixed value of the independent variable ξ_i . However, if a linear model, such as $Y_{ij} = \mu + X_i\beta + \epsilon_{ij}$, is fit to the data of this study, there appears to be no means of separately estimating μ , β , and the variances of X and Y . For this reason classical regression procedures in which the X_i are considered fixed will be used.

Model I assumes that the regression of shore-based to aerial sea otter counts passes through the origin. Intuitively, this is a logical assumption because one would expect shore-based and aerial counts in a given area to be related by a simple ratio. However, at Amchitka Island there are large numbers of sea otters in all sufficiently large coastal segments, and therefore the regression function near the X and Y axes is only conceptual. Realistically, shore-based counts and aerial counts within relatively large study areas [i.e., about 10 miles (16 km) of coastline] are both much greater than zero, and a best-fit line through these points may well depart significantly from the origin.

By model I,

$$Y_i = X_i\beta_1 + \epsilon_i \quad (1)$$

where Y_i = i th shore-based sea otter count (estimated population number within study area)

X_i = i th aerial sea otter count within the study area

β_1 = slope of the regression equation

ϵ_i = error

For an estimate of the total number of sea otters at Amchitka (Y_0), it is sufficient to substitute X_0 into Eq. 1 to give $\hat{Y}_0 = X_0\beta_1$, where X_0 is

Table 2—Numbers of Sea Otters Counted Within Areas Indicated in Fig. 3 During Island-Wide Aerial Surveys

Subunit Pacific	6/5/72		8/23/72		8/25/72		9/11/72	
	No.	Proportion of subtotal	No.	Proportion of subtotal	No.	Proportion of subtotal	No.	Proportion of subtotal
1	31	0.0274	16	0.0068	40	0.0223	55	0.0244
2	79	0.0697	67	0.0284	43	0.0240	64	0.0284
3	165	0.1456	103	0.0436	177	0.0989	96	0.0426
4	25	0.0221	27	0.0114	110	0.0615	82	0.0364
5	99	0.0874	300	0.1270	30	0.0168	223	0.0990
6	39	0.0344	70	0.0296	10	0.0056	84	0.0373
7	78	0.0688	177	0.0749	34	0.0190	120	0.0533
8	66	0.0583	147	0.0622	35	0.0196	113	0.0502
9	44	0.0388	83	0.0351	25	0.0140	156	0.0693
10	46	0.0406	66	0.0279	50	0.0279	77	0.0342
11	59	0.0521	139	0.0588	113	0.0631	66	0.0293
12	28	0.0247	110	0.0466	229	0.1279	84	0.0373
13	55	0.0485	103	0.0436	104	0.0581	26	0.0115
14	30	0.0265	132	0.0559	48	0.0268	158	0.0702
15	22	0.0194	76	0.0322	52	0.0290	42	0.0187
16	23	0.0203	36	0.0152	54	0.0302	85	0.0377
17	44	0.0388	70	0.0296	87	0.0486	55	0.0244
18	45	0.0397	97	0.0410	128	0.0715	111	0.0493
19	35	0.0309	176	0.0745	99	0.0553	97	0.0431
20	48	0.0424	76	0.0322	52	0.0290	137	0.0608
21	72	0.0635	292	0.1236	270	0.1508	321	0.1425
Subtotal	1133		2363		790		2252	
Percent of total	44		60		51		56	

Subunit Bering	6/5/72		6/7/72		8/23/72		8/25/72		9/1/72	9/11/72	
	No.	Proportion of subtotal	No.	Proportion of subtotal	No.	Proportion of subtotal	No.	Proportion of subtotal	No.	No.	Proportion of subtotal
22	84	0.0587	135	0.0881	171	0.1059	120	0.0692	101	168	0.0939
23	50	0.0349	53	0.0346	65	0.0415	37	0.0213	27	33	0.0184
24	69	0.0482	63	0.0411	54	0.0344	84	0.0484	46	49	0.0274
25	68	0.0475	66	0.0431	81	0.0517	91	0.0525	50	64	0.0358
26	71	0.0496	60	0.0392	95	0.0606	50	0.0288	51	42	0.0235
27	45	0.0314	48	0.0313	20	0.0128	20	0.0115	41	52	0.0291
28	41	0.0287	81	0.0529	24	0.0153	32	0.0185	23	58	0.0324
29	45	0.0314	15	0.0098	37	0.0236	50	0.0288	35	43	0.0240
30	98	0.0685	195	0.1273	149	0.0950	129	0.0744	88	132	0.0737
31	31	0.0217	34	0.0222	62	0.0395	101	0.0582	90	93	0.0520
32	51	0.0356	70	0.0457	30	0.0191	87	0.0502	53	45	0.0251
33	59	0.0412	54	0.0352	82	0.0523	78	0.0450	46	123	0.0687
34	38	0.0266	59	0.0385	18	0.0115	41	0.0236	22	63	0.0352
35	43	0.0300	28	0.0183	13	0.0083	41	0.0236	26	50	0.0280
36	40	0.0280	33	0.0215	16	0.0102	104	0.0600	39	77	0.0430
37	67	0.0468	47	0.0307	123	0.0784	60	0.0346	39	87	0.0486
38	42	0.0294	58	0.0379	104	0.0663	35	0.0202	53	100	0.0559
39	69	0.0482	125	0.0816	8	0.0051	149	0.0860	98	119	0.0665
40	37	0.0259	45	0.0294	11	0.0070	25	0.0144	7	20	0.0112
41	7	0.0049	4	0.0026	10	0.0064	28	0.0161		18	0.0101
42	184	0.1286	135	0.0881	106	0.0676	137	0.0790		140	0.0782
43	20	0.0140	14	0.0091	43	0.0274	22	0.0127		27	0.0151
44	37	0.0259	73	0.0479	76	0.0485	57	0.0329		79	0.0441
45	135	0.0943	37	0.0242	170	0.1084	156	0.0900		108	0.0603
Subtotal	1431		1532		1568		1734		935	1790	
Percent of total	56				40		49			44	
Total	2564				3931		3524			4042	

Table 3—Comparison of Shore-Based and Aerial Sea Otter Counts from Selected Study Areas Around Amchitka Island*

Date	Viewing conditions	Shore based	Aerial	Study area†	Shore-based to aerial count ratio
5/20/72‡	II (rain)	192	50	A‡	3.84§
5/21/72	II (clear)	641	191	D	3.36§
5/25/72	II	346	172	A	2.01
5/25/72	II—III	420	215	D	1.95
5/26/72	II	343	185	C	1.85
5/27/72	II	382	221	A	1.73
5/29/72	I	602	186	D	3.24
5/29/72	I—II	452	202	A	2.24
6/07/72	I	450	288	A	1.56
8/24/72	I	521	297	A	1.75
8/24/72	I	797	436	D	1.83
8/31/72	II	501	348	A	1.44
		Mean	1.96 ± 0.17 n = 10		

*No data were obtained from area B.

†See Fig. 2 for location of these study areas.

‡Only segments 1 to 4 counted.

§Not used in later analysis.

the island-wide aerial count (4042 sea otters). The 4042 sea otter count was the highest island-wide aerial count. I believe this count is most nearly representative of aerial counts made within study areas under near ideal viewing conditions. With the standard least-squares technique of parameter estimation (i.e., by evaluating the normal equations), $\hat{\beta}_1 = 1.82$. An analysis of variance of model I is given in Table 4.

Model II assumes that the regression line is linear but not constrained to pass through the origin. By model II,

$$Y_i = \mu + X_i\beta_2 + \epsilon_2 \quad (2)$$

where μ is the Y intercept, β_2 is the slope of the regression equation in model II, and ϵ_2 is the residual error in model II.

Equation 2 is an estimator of shore-based sea otter counts (or the estimated number of sea otters) within the i th study area. If μ proves significant, the $\hat{Y}_i$ must be summed around the entire island rather than simply substituting X_0 for X_i (as in model I) because μ must be accounted for on an island-wide basis. Thus

$$\hat{Y}_0 = \sum_{k=1}^n (\hat{\mu}_k + X_k\hat{\beta}_2) = n\hat{\mu} + \sum_{k=1}^n X_k\hat{\beta}_2$$

where $\mu_1 = \mu_2 = \dots = \mu_n$ and n is the number of segments of coastline (which are of similar length to the study areas) contained within the island

perimeter. With this method the line is not being extrapolated beyond the data but rather is the sum of interpolated values. The analysis of variance of model II is given in Table 4. Elements of the parameter vector (i.e., μ and β_2) are estimated by the normal equations. To test the significance of μ , I set up two hypotheses: $H_0, \mu = 0$, and $H_a, \mu \neq 0$. By H_0 [total sum of squares - (sum of squares $\hat{\beta}_2$ + sum of squares ϵ_2)]/(mean square ϵ_2) is distributed as $F_{1,8}$. The level of significance was arbitrarily chosen at 0.05; thus $P(F_{1,8} \geq 5.32) = 0.05$. Because 253 (the observed value of F) $\gg$ 5.32, H_0 was rejected, and model II was used to estimate the island-wide population number. From model II, $\hat{Y}_0 = 1581 + (1.20)(4042) = 6432$ sea otters (an arithmetic error has been pointed out to me in my earlier estimate of 6918 sea otters). Under stated assumptions of the model, this statistic is an unbiased estimate of the number of sea otters at Amchitka. A 95% confidence interval around this estimate is 5226 to 7638 animals.

Figure 6 shows 30- and 50-fathom (55- and 91-m) depth contours around Amchitka. Within the 30-fathom depth contour, there are 38 square miles (or 35% of the total area) on the Bering Sea side of Amchitka and 72 square miles (or 65% of the total area) on the Pacific Ocean side (Kenyon, 1969, p. 150). Data from island-wide population surveys suggest that a greater proportion of the sea otter population lives on the Pacific Ocean side than on the Bering Sea side of the island. On Aug. 23, 1972, when viewing conditions were comparable on both sides of Amchitka for counting sea otters, 40% of the animals were observed on the Bering Sea side and 60% were observed on the Pacific Ocean side. On Sept. 11, 1972, the day of the highest aerial count of the entire island, 44% of the animals were seen on the Bering Sea side and 56% were seen on the Pacific Ocean side. Thus the distribution of the population between the two

Table 4—Analysis of Variance of Model I and Model II Regressions of Shore-Based vs. Aerial Sea Otter Counts

Source	Degrees of freedom	Sum of squares	Mean square
Model I			
Due to $\hat{\beta}_1$	1	2384250	11366
Due to ϵ_1	9	102298	
Total	10	2486548	
Model II			
Due to $(\hat{\mu}, \hat{\beta}_2)$	2	2412847	9213
Due to ϵ_2	8	73701	
Total	10	2486548

Fig. 6—The 30- and 50-fathom depth contours at Amchitka Island.

sides of Amchitka is similar to the distribution of available habitat.

On the basis of Kenyon's (1969) discussion and my own observations, to estimate roughly the sea otter density at Amchitka, I assumed that most of the sea otters are unable to dive deeper than 30 fathoms (55 m). I also assumed that the entire area within a particular depth contour is usable sea otter habitat and of equal value to the population. Two factors which also may be important but which I have chosen not to consider in the interest of simplicity (and lack of information) are variation in productivity as a function of depth and heterogeneity of substrate type and configuration.

I estimate that 6432 sea otters live at Amchitka, 60% of which are on the Pacific Ocean side and 40% of which are on the Bering Sea side of the island. By assuming that these animals occur within the 30-fathom (55-m) depth contour, I calculated an island-wide sea otter density of 59 animals per square nautical mile (17 per square kilometer) of habitat. This estimate may be divided into 68 animals per square mile (20 per square kilometer) of habitat in the Bering Sea and 54

animals per square mile (16 per square kilometer) of habitat in the Pacific Ocean.

Variable weather conditions and variations in the distribution of sea otters are probably the two most important factors influencing the numbers of animals counted during aerial surveys. I previously mentioned that flat glassy calm seas and high cloud cover provide the most ideal counting conditions. That the distribution of animals is also important is evident from the results of two island-wide counts. On Aug. 25, 1972, we counted 3524 sea otters (island wide) with near ideal viewing conditions. On Sept. 11, 1972, we observed 4042 animals with viewing conditions of light surface chop and occasional rain. On August 25 sea otters were scattered throughout the kelp beds and offshore areas whereas on September 11 large numbers of otters were bunched at the outer edges of kelp beds. Even though superior viewing conditions existed on August 25, a greater island-wide sea otter count was obtained on September 11 because the animals occurred in groups and thus were easier to count than on August 25 when they were more dispersed.

DISCUSSION

Population Time Budget

Prolonged rough seas certainly cause many sea otters to seek shelter near shore (Lensink, 1962; Kenyon, 1969). However, I have observed individuals feeding in extremely rough water, and I also have noted that the number of animals hauled out or concentrated in sheltered areas during severe storms never approaches the number of animals known to inhabit those same areas. I therefore conclude that a substantial portion of the sea otter population at Amchitka is able to maintain itself in the open sea despite inclement weather. This conclusion is supported by the observation that certain sea otter populations in other geographical areas (i.e., north of Unimak Island in southern Bristol Bay) rarely, if ever, come ashore (K. Schneider, personal communication). However, the severe storms common to the Aleutian Islands make observational work difficult, and undetected changes in population behavior may accompany changes in the weather. On calm days at least, I have seen sea otters at distances of about 2 miles from shore.

The similar diurnal time patterns and percentages of feeding activity during summer and winter (Fig. 4) suggest either that sea otters feed during hours of darkness in winter or that less food is consumed by the population during winter than during summer. Because of their high and continual nutritional requirements (Kenyon, 1969; Morrison, Rosenmann, and Estes, 1974; Morrison, Rosenmann, and Estes, Chap. 23, this volume), I believe that decreased food consumption over long periods of time is unlikely. Kenyon (1969) presented evidence that sea otters have well-developed tactile and olfactory senses, and thus it is not inconceivable that they can feed in the absence of light. However, no data are available which prove that sea otters are nocturnal feeders. Therefore the significance of Fig. 4 remains unresolved.

The apparent increase in grooming during winter over summer (Fig. 4) probably is not real but probably is an artifact of limited offshore visibility during winter months. At long distances grooming animals are difficult to distinguish from those which are feeding. Therefore a smaller percentage of the population was identified as grooming during summer months.

A limitation of the observational technique which I have used is that a superficial knowledge of the structure and behavior of the local sea otter population is required before an assumption can be made that the area is representative of the entire population. For example, resting sea otters tend to

congregate into groups at traditionally used areas. If these areas are not included in the observation areas, a bias will exist toward feeding activity. Conversely, when poor viewing conditions exist, a bias toward resting activity would be observed in an area where sea otters are resting. For this reason the technique is valid only on days when visibility is such that a sufficiently large (representative) expanse of ocean can be observed. My opinion is that this generally should include at least several miles of coastline. Furthermore, home range, territoriality, individual movements, and factors that relate to spatial strategies of sea otters are not well understood. In view of these unknowns, any supposition that a representative segment of the population is being observed should, at the very least, be considered with skepticism.

In the results section I mentioned a small discrepancy between my data and data collected by Kenyon (1969) on the percentage of time sea otters budget for feeding. Differences between my data and Kenyon's may be the result of different study techniques or real changes in feeding activity since 1955 when his data were collected. As I suggested earlier, the differences that my data indicate between summer and winter feeding activity probably do not represent changes in population foraging strategies.

In contrast to Amchitka, the sea otter population at Attu is far below equilibrium density. This probably results in an abundant food supply for those animals living at Attu. Sea otters observed feeding at Attu were all near shore [I estimated 200 yards (183 m) or less], and they moved only small distances while feeding. Feeding sea otters at Amchitka frequently are scattered to over a mile from shore, and often they move considerable distances during a feeding period. These behavioral differences are probably related to an abundant near-shore food supply at Attu. Conversely, the sea otter food supply at Amchitka probably is being maximally exploited. Sea otters must therefore search more and dive to their maximum capabilities to obtain sufficient food under these circumstances. This probably results in greater amounts of time spent in foraging activity by sea otters at Amchitka compared with those at Attu. Although I have no quantitative data from Attu to compare with the diurnal feeding pattern at Amchitka, most of the animals I saw at Attu were resting.

Sea Otter Population Estimates

For a parameter estimate $\hat{\theta}$ to be of practical utility, it should be unbiased and relatively precise. By definition, a parameter estimate is unbiased if the expected value of that estimate $E(\hat{\theta})$ is equal to

the parameter θ for all θ . In this study θ is the total number of sea otters at Amchitka Island. Bias is the difference between the expected value of the parameter estimate and the true value of the parameter [i.e., $E(\hat{\theta} - \theta)$; Hoel, 1971]. Direct population counts are almost always biased low as estimates of population numbers because some individuals are invariably missed.

An estimate should also be relatively precise. From a set of estimators of θ , the estimate that has minimum variance is referred to as the best estimate. Frequently the estimate with minimum variance is not unbiased and thus perhaps not best in terms of study objectives. Therefore, when one selects an estimation technique, the tolerability of bias and lack of precision should be carefully considered. Obviously estimates with large and unknown bias are only valuable as population indexes and are relatively worthless as estimates of population numbers. Conversely, highly variable estimates, even though they may be unbiased, are of little value unless a large number of repetitions are available. Furthermore the variance of an estimate can be determined through repetition of the sample whereas bias may remain obscure unless specific techniques are developed to evaluate its magnitude and direction. For this reason many investigators in wildlife biology are intuitively more aware of variance than bias. Thus the concepts of bias and precision are critical, and they must be considered carefully when evaluating population estimates. I will consider the sea otter population at Amchitka with these concepts in mind.

The first large-scale studies of sea otters in Alaska were done by the U. S. Fish and Wildlife Service. Usually they censused sea otters from a DC-3 aircraft flying at about 120 knots (222 km/hr) between altitudes of 200 and 400 ft (61 and 122 m). Two observers in the cockpit counted sea otters. From these aerial counts the number of sea otters at Amchitka was estimated to be from about 1500 to 2500 animals between the years 1949 and 1965 (Kenyon, 1969).

On the basis of aerial counts and counts made from headlands with binoculars and a spotting scope, Lensink (1962) estimated that between 4000 and 7000 sea otters lived at Amchitka in 1956. These estimates were dismissed by Kenyon (1969) and apparently were not considered seriously in subsequent work.

Helicopters were first used as vehicles from which to count sea otters by the U. S. Fish and Wildlife Service in 1968. The technique and preliminary results were discussed by Spencer (1969). A single observer seated beside the pilot counted sea otters as the aircraft was flown at about 150 ft

(46 m) altitude and at a maximum speed of about 70 knots (130 km/hr). In 1970, 3927 sea otters were counted during island-wide censuses. From this count the population at Amchitka was estimated at slightly over 4000 animals (U. S. Fish and Wildlife Service, unpublished data).

Stephan (1971) used oblique infrared color photography to estimate the number of sea otters at Amchitka. He photographed population concentrations with a helicopter-mounted camera and visually counted additional scattered animals. This technique led him to estimate that Amchitka Island contained . . . "as many but not more than 2800 sea otters" during 1969.

The primary advantage of fixed-winged aircraft (airplanes) as census vehicles is that large areas can be covered in relatively short periods of time. Considering the hundreds of miles of shoreline inhabited by sea otters, from the western Aleutian Islands to Prince William Sound, this technique was most practical for early U. S. Fish and Wildlife Service studies. The primary contribution of these studies was the establishment of trends in sea otter distribution and density over the entire Alaskan range of the species. Many animals undoubtedly were missed because of limitations imposed by the large rapidly flying aircraft.

Kenyon (1969) concluded from his studies that the majority of sea otters live within the 20-fathom (37-m) depth contour, and rarely they are found in waters as deep as 30 fathoms (55 m). Although there are occasional reports of sea otters diving in deeper areas (K. Schneider, personal communication), Kenyon's conclusion defines the area within which counting efforts should be concentrated. This conclusion also implies that coastal areas where the subtidal platform descends gradually will be more difficult to census than areas where the sea otter habitat is narrower.

I believe that the number of sea otters estimated from this study was biased low. In view of techniques and the scope of these investigations, no data were collected with which to estimate the magnitude of bias. Additionally, the relative precision of these estimates is unknown because the censuses were not replicated over sufficiently short time periods.

Data obtained from U. S. Fish and Wildlife Service helicopter censuses which began in 1968 are summarized in Table 5. Only maximum counts are included for each survey period.

Watson, Jolly, and Graham (1969) showed that helicopters are significantly better vehicles than airplanes from which to census terrestrial mammal populations. The primary advantages of helicopters over airplanes as vehicles for counting sea otters are greater maneuverability and slower flying speed.

Table 5—Summary of Aerial and Photogrammetric Sea Otter Counts of Amchitka Island Made Between 1968 and 1972

	Maximum count				
	1968	1969	1970	1971	1972
Bureau of Sport Fisheries and Wildlife*	2302(7)†		3927(5½)†	3241(1)†	
Battelle Memorial Institute‡		2354	2773		
University of Arizona*					4042(4)†

*Visual counts.

†Number in parentheses is the number of counts.

‡Visual and photographic counts.

Thus kelp beds, offshore islands, and otherwise inaccessible areas can be thoroughly searched. Consequently estimates of sea otter numbers at Amchitka Island during these studies are almost twice as large as earlier estimates obtained with airplanes.

Because of the time interval between Kenyon's study and more recent efforts by the U. S. Fish and Wildlife Service, differences in population estimates might be construed as an increase in population size. There is no other evidence to support this argument. In fact, Kenyon (1969) presented data which suggest that the sea otter population at Amchitka Island was limited by food availability during the time of his early studies. I believe that the reported differences in sea otter population numbers are primarily the result of reduced bias. However, there were no attempts during either of these studies (other than by intuition) to statistically estimate bias, and even these later estimates probably greatly underestimated the size of the sea otter population at Amchitka.

All direct visual counts of sea otter populations are distinctly unprecise (i.e., the counts, when repeated, are highly variable). This high variability apparently is correlated primarily with variable viewing conditions and an unpredictable spatial distribution of sea otters. Poor viewing conditions are caused by inclement weather, which prevails almost continuously in the Aleutian Islands. Strong winds may blow at any time of the year, and fog and rain are common during calmer months. Sea otters are most easily seen when seas are glassy calm and the air is clear with a high unbroken overcast. Such ideal viewing conditions are never common but prevail most frequently during late May through early June and late August through late September or early October.

Sea otters also tend to congregate into large groups at times and to scatter in a more random spatial distribution at other times. Clumped distributions of sea otters tend to increase the size of the total counts.

A summary of the sea otter counts that were obtained at Amchitka Island from infrared color photogrammetry is also given in Table 5. The advantage of this technique apparently is a more precise estimate of the population number. Presumably, infrared photography reduces the counting variability due to the effects of weather. This would be an obvious advantage in the Aleutian Islands. However, there are also several disadvantages. Population numbers estimated by this technique were considerably lower than direct visual counts from a helicopter during the same years. Thus, although possibly there is a gain in precision from the photogrammetric technique, it is accompanied by increased bias. Perhaps with further improvements, specifically the development of a method to estimate and correct for bias, photographic or other remote sensing techniques may prove valuable. There are, however, additional disadvantages. The cost is very high. A large amount of film would be required to cover all the sea otter habitat between shore and the 30-fathom (55-m) depth contour, even along relatively small expanses of coastline. Species are also difficult to identify from photographs (i.e., sea otters may be confused with harbor seals).

With a spotting scope from shore-based stations, Lensink (1962) counted about 1.75 times more sea otters in a given area than he was able to see through binoculars. This suggests that many animals at Amchitka Island are distributed far offshore. Lensink's estimate of the number of sea otters at Amchitka Island has been criticized on the basis of overlap between contiguous counting

areas and localized movement of animals. The U. S. Fish and Wildlife Service observers believed that they were seeing 50 to 75% of the sea otter population during counts from airplanes and that Lensink's estimates were biased high (Kenyon, 1969). I believe that Lensink's technique, although not statistically designed to provide an unbiased estimate, applies a logical estimate of correction for bias. The lack of replication precludes any comment on precision.

There are several disadvantages to the shore-based counting technique. During Lensink's study the lack of a helicopter necessitated travel by foot between counting areas. This was a time-consuming process which limited the amount of coastline that could be covered in a single day. Simultaneous shore-based and aerial counts of the same area also were not possible during the period of Lensink's work, thus precluding the development of an index by which shore-based and aerial counts could be compared.

Counting from shore offers the advantage that an adequate amount of time can be spent thoroughly searching for sea otters in a given area. This is important when one considers the large percentage of time spent feeding (and therefore diving) by sea otters at Amchitka. Even during periods of minimum feeding activity, approximately 30% of the population is beneath the surface at any given instant (see Fig. 5). An instantaneous observation of a given area during this time, such as a photograph, will therefore detect approximately 70% of the sea otters in that area. If we assume that individual dives are independent events and that the duration of dives is approximately constant among individuals, the cumulative percentage of surfaced animals will increase approximately as a linear function of time. Furthermore, this cumulative percentage will approach 100% after a time equivalent to the duration of a dive. Thus photographs (or other instantaneous observations), no matter what their quality or how inclusive their area, will never detect more than about 70% of the sea otter population at Amchitka Island. Visual aerial counts are also biased low by the effect of diving animals, but by $100 t/(s + \mu)$ percent less than are instantaneous observations (McLaren, 1961), where t is the observation time of a given area, s is the surface time of sea otters, and μ is the diving time of sea otters. Also, the observation time required to correct for bias due to diving activity will be greater in deep water (where μ and s are relatively long) than in shallower water (where μ and s are shorter).

In summary, aerial counts are biased estimates of the number of sea otters at Amchitka Island because a large percentage of the population is

submerged at any given time. Animals which are on the surface but which simply are not seen contribute further to low bias. Thus I believe even the highest aerial counts are biased low by 30% or more. Shore-based observations on days when surface visibility is very good provide a crude means by which to account for this bias.

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Ecological Interactions Involving the Sea Otter

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A comparison of western Aleutian Islands with and without sea otters shows this species to be important to the organization of the nearshore communities. Sea otters control herbivorous invertebrate populations and indirectly affect wave exposure and the composition of the rocky

intertidal community. The removal of sea otters causes increased herbivory and ultimately results in destruction of macrophyte associations. Our observations suggest that a dense sea otter population indirectly supports fauna associated with macrophyte primary productivity.

One of the most striking features of the nearshore community at Amchitka Island is the dense population (approximately 6400 animals) of sea otters, *Enhydra lutris* (Estes and Smith, 1973; Estes, Chap. 21, this volume). The estimated density of 17 sea otters per square kilometer (59 animals per square nautical mile) of feeding habitat, waters 55 m (180 ft) or less in depth (Kenyon, 1969), is one of the highest concentrations of this predator ever recorded (Estes and Palmisano, 1974; Estes, Chap. 21, this volume; Lowry and Pearse, 1973; Kenyon, 1969; and Odemar and Wilson, 1969). The high density of sea otters and the importance of predation in structuring communities, as noted by Paine (1966; 1971), Harper (1969), and Addicott (1974), suggest a major role for the sea otter in the organization of the nearshore community at Amchitka Island.

NEARSHORE COMMUNITY

Definition. For purposes of this discussion, the nearshore community comprises that group of organisms (marine, avian, and terrestrial) inhabiting either side of the shoreline and dependent either exclusively on the marine environment or on both the marine and terrestrial environments for some resource. For convenience the marine portion of this community has been divided into two areas:

(1) the intertidal area, or that part of the shore alternately flooded by water and exposed to air by the rhythmic movements of the tides; and (2) the subtidal area, or that area from lowest lower low water to the 55-m (180-ft) depth contour.

FACTORS CONTROLLING THE STRUCTURE OF MARINE COMMUNITIES

Island Biogeography. To properly understand the marine community of Amchitka, we must realize that the study of island communities presents a special problem in the explanation of community composition. Although environmental factors operate here as at the edge of continents, species richness, immigration rates, and extinction rates are different on islands (MacArthur and Wilson, 1963; 1967; Carlquist, 1965; 1973). The number and kind of species on islands are directly related to the dispersal abilities of organisms, to the distance from source areas, and to island size (MacArthur and Wilson, 1967). Large islands and islands nearer to source areas have more species than do small or distant islands. Thus organisms may be absent from islands simply because they failed to arrive or because, if the island is small, they have become extinct. As in all geographical areas, physical and biological factors also may prevent colonization.

Not all work on island biogeography has been theoretical. Results of field studies (Preston, 1962; Simberloff and Wilson, 1970; Diamond, 1969; 1973) are in agreement with most theoretical arguments. However, most work has been on

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terrestrial groups of organisms and may not be applicable to marine communities.

Tidal amplitude affects intertidal community structure (Ricketts and Calvin, 1968). It also tends to be less extreme on islands than on continents, a situation that may produce differences in intertidal communities between islands and continents. In terrestrial communities increased island size increases species richness through the direct effect of area and through increased physical heterogeneity. In marine communities increased island size probably affects species diversity but not necessarily because of increased physical heterogeneity. There is little reason to expect the intertidal area of a large island to be physically more heterogeneous than a small island. The intertidal environment is not extensive, vertically or horizontally, and does not have the same possibilities for physical heterogeneity as does the more expansive terrestrial environment.

The reproductive strategies of many marine organisms strongly influence their ability to disperse and colonize (Vance, 1973; Strathmann, 1974). For example, organisms with pelagic larvae frequently may reach oceanic islands. However, they may fail to colonize because the same currents on which they arrived also may remove their larvae. These species might be successful colonists only in embayments or on coastlines devoid of currents or otherwise where new larvae arrive periodically. Organisms with nonpelagic larvae are poor dispersers, but, once they reach an island, they should colonize more successfully and thus should be more common on continental islands, in archipelagoes, or on older islands. More simply stated, species with pelagic larvae may be capable of rapid and extensive colonization but probably are subject to high extinction rates. Conversely, nonpelagic larvae may restrict or inhibit dispersal but probably facilitate low extinction rates.

Because Amchitka is an oceanic island (i.e., its biota is not a relict from a continental land mass), the composition of its marine community is determined primarily by dispersal capabilities of marine organisms and secondarily by physical and biological factors. Organisms may be absent from Amchitka because of local extinctions caused by stochastic events (i.e., severe weather and food shortage) and by coactive forces (competition and predation). Extensive predation by dense populations of sea otters may lead to local extinction of prey species and associated communities. Competition from dense populations of sea otters may cause other species to become locally extinct. Where sea otters themselves become locally extinct, e.g., the Near Islands, organisms and com-

munities associated with dense populations of this predator may also disappear. These and other factors will be considered in the assessing of the role of sea otters in the community ecology of Amchitka.

Physical and Biological Factors. For years physical factors were considered to be largely responsible for the distribution and composition of plants and animals in marine communities. This concept was especially popular for intertidal communities where physical and chemical tolerances of plants and animals were thought to correspond to physical and chemical ranges of environmental factors, such as wave shock, substratum, temperature, and dissolved gases, that existed at different tidal levels. Thus the resulting assemblages of plants and animals into vertical zones were believed to result primarily from air exposure within different vertical levels in the intertidal area (Doty, 1946; Hewatt, 1937; Newell, 1970). Light was considered responsible for the distribution of subtidal algal associations (Neushul, 1965; 1967; Kain, 1966; Crossett, 1967; Blinks, 1955; Haxo and Blinks, 1950).

Recent works in the marine rocky intertidal area by Connell (1961a; 1961b; 1970; 1972), Paine (1966; 1969; 1971), Dayton (1971), and others have aptly demonstrated that biological factors (predation and competition) are extremely important in influencing composition and structure in rocky intertidal communities. Connell contends that the upper limits of plants and animals are probably determined by physical factors and that lower limits are set by biological factors. Vadas (1968) and Paine and Vadas (1969) have demonstrated that grazing affects the distribution of subtidal algal associations.

Another advance in marine ecology has been the recognition of key species responsible for determining structures and dynamic relationships within communities. Paine (1969) has referred to these as "keystone species." They are usually predators or herbivores whose feeding activities profoundly affect community structure.

Effects of Grazing on Marine Vegetation. Destruction of subtidal and intertidal kelp and sea-grass beds as a result of overgrazing by dense populations of sea urchins has been observed over a wide geographical range. Himmelman and Steele (1971) believe that sea urchins are responsible for the scarcity of noncoralline algae in many coastal areas of Newfoundland. Kain and Jones (1965) stated that grazing by sea urchins determines the vertical distribution of algae on the Isle of Man. Kitching and Ebling (1961) and Jorde and Klavesstad (1963) found that the distribution of dense sea

urchin populations and abundant algal growth were almost mutually exclusive in the sublittoral area of the northeastern Atlantic Ocean. Dayton, Rosenthal, and Mahan (1973) reported a reduced macrophyte association due to sea urchin grazing in the Chilean archipelago. The reduction of benthic macrophyte populations by sea urchin grazing along the coast of California has been described by North (1965) and in the Gulf of Mexico by Camp, Cobb, and Van Breedveld (1973). The removal of sea urchins by experimental manipulation (Paine and Vadas, 1969; Kitching and Ebling, 1961) and by accidental oil spills (Nelson-Smith, 1968) has resulted in the development of extensive beds of marine vegetation. Because community structure differs in the presence or absence of these beds (Limbaugh, 1955; Kitching and Ebling, 1961; McLean, 1962; North, 1965; Quast, 1968) and because prey density in the marine environment can be significantly influenced by predation (Paine, 1966; 1971; Porter, 1972), the structure of a marine community should be affected by the intensity of herbivore predation.

SEA OTTERS

Trophic Level, Food Habits, and Energy Requirements. The sea otter is a top carnivore in the nearshore trophic-dynamic ecosystem at Amchitka Island. It is also an opportunistic feeder, preying primarily on benthic invertebrates, especially sea urchins, and bottom fishes (Lensink, 1962; Kenyon, 1969; Burgner and Nakatani, 1972). Adult captive sea otters require 20 to 23% of their body weight in food daily, and in the natural environment energy requirements are perhaps even greater (Kenyon, 1969; Morrison, Rosenmann, and Estes, 1974; Morrison, Rosenmann, and Estes, Chap. 23, this volume). In view of the preceding discussion and of the abundance of sea otters at Amchitka and considering that the average sea otter weighs about 23 kg (50 lb) (Kenyon, 1969), we estimate that about 35,000 kg km⁻² year⁻¹ (200,000 lb square mile⁻¹ year⁻¹) of animal biomass is removed by the sea otter in foraging activities (Estes and Palmisano, 1974).

HYPOTHESIS OF SEA OTTER PREDATION

We suggest that sea otters affect the structure of the nearshore community at Amchitka, and their presence or absence is the prime cause for differences observed between nearshore communities at Amchitka, Adak, Shemya, and Attu Islands (Table 1 and Fig. 1). Our hypothesis holds that a dense population of sea otters controls sea urchins, which, when uncontrolled, can consume and destroy large quantities of kelp. The resultant re-

lease from grazing pressure permits an increase in the size of nearshore and intertidal kelp beds and associated communities (Jones and Kain, 1967; Paine and Vadas, 1969). Thus we hypothesize that sea otters are responsible for the extensive subtidal and intertidal kelp beds and for the lack of dense populations of certain benthic invertebrates in the subtidal and intertidal communities at Amchitka.

A corollary to this hypothesis is that a small population or the absence of sea otters enables the sea urchin population to increase, which in turn causes a significant reduction in the size of kelp beds and associated communities. The absence of large offshore kelp beds increases exposure to the intertidal area because all wave energy now reaches shore. Increased herbivory and exposure provide open patches in intertidal kelp beds which permit settling and establishment of sessile invertebrate populations.

Thus we hypothesize that the primary influence of sea otter predation is on subtidal communities; however, the intertidal area also is directly affected by sea otter predation at high tide. Indirectly, sea otter predation affects intertidal communities by reducing grazing pressure on subtidal-intertidal transients, by reducing recruitment, and by decreasing the physical shock of wave impact by permitting the presence of large kelp beds.

STUDY AREA

Location and Description

Field observations were made at Amchitka periodically from October 1970 to August 1973, at Shemya for 1 week each in September 1971 and July 1972, at Attu for 4 days in July 1972, and at Adak for 9 days in September 1972. An estimate of sea otter population at each island studied is given in Table 2. All these islands except Adak have well-developed intertidal rock benches. Only Amchitka has extensive offshore kelp beds and large accumulations of drift kelp [up to 0.7 m (2.3 ft) deep and 7 m (23 ft) wide] along the shoreline. The climate, sea conditions, tidal ranges, and mean tidal levels are comparable at all four islands (U. S. Department of Commerce, Coast and Geodetic Survey, 1968; personal observation).

Amchitka. The most prominent physical features of the marine environment of Amchitka (Fig. 2) are the uniform maritime climate (Armstrong, Chap. 4, this volume) and the extensive intertidal rock platform (bench) that extends seaward from the base of cliffs surrounding much of the perimeter of the island (Gard, Chap. 2, this volume; Lebednik and Palmisano, Chap. 17, this volume).

Table 1—Major Biological Features of Nearshore Communities at Four Western Aleutian Islands, 1971–1973

Island	Sea otter population	Sea urchin		Benthic algal beds	Barnacle and mussel populations on intertidal bench
		Size	Population		
Amchitka	Dense	Small	Sparse	Extensive and little grazed	Sparse
Adak	Dense	Small	Sparse	Extensive and little grazed	Sparse
Attu	Sparse	Large	Dense	Sparse and heavily grazed	Dense
Shemya	None	Large	Dense	Sparse and heavily grazed	Dense

Fig. 1—Map of western Aleutian Islands showing the Near and Rat Island groups.

The landward edge of the bench is almost always adjacent to cobble or sand beaches, but at times it terminates against rock faces. The bench is not continuous around the island but is interrupted by cobble or sand beaches. The elevation of the bench is approximately mean sea level (Powers, Coats, and Nelson, 1960). The bench is best developed along the Pacific Ocean side of the island where it is 100 m (330 ft) wide in places (Fig. 3). The bench is flat, porous, and soft enough in most places (except at headlands) to fasten nails with a hammer and even to be pulled apart by hand. Channels, tide pools, boulders, and sea stacks (Lebednik and Palmisano, Chap. 17, this volume) are not abundant but do occur.

Headlands and areas with narrow or no intertidal benches are more exposed to wave action

than are bays, harbors, and areas with a wide bench. Offshore kelp beds also protect the shoreline from wave action, as Moore (1958), Lewis (1964), and MacGinitie and MacGinitie (1968) have observed elsewhere. These more-protected areas have more silt deposition than do areas exposed to waves. In general, the intertidal bench on the Bering Sea is narrower (Fig. 4) and thus more exposed than the intertidal bench on the Pacific Ocean, even though the Pacific Ocean is more turbulent than the Bering Sea (Gard, Chap. 4, this volume).

Tidal range is approximately +2.3 to -0.7 m (+7.5 to -2.3 ft). Mean tide level is approximately +0.5 m (+1.6 ft). Spring tides are diurnal (one high and one low per day). Neap tides are mixed semidiurnal (two highs of unequal levels and two

Table 2—Sea Otter Counts, Estimates, and Densities at Four Western Aleutian Islands, 1932–1972

Year	Otters counted	Otters estimated	Otters estimated per square kilometer of habitat	Source
Attu				
1932*	0	0	0	Kenyon, 1969
1959	0	0	0	Kenyon, 1969
1965	13	ND†	ND	Kenyon, 1969
1972	25	ND	ND	Estes and Smith, 1973
Shemya				
1932*	0	0	0	Kenyon, 1969
1959	0	0	0	Kenyon, 1969
1965	10	ND	ND	Kenyon, 1969
1971	0	0	0	Personal observation
1972	0	0	0	Personal observation
Amchitka (377 km ² of habitat) ‡				
1936	814	3100	8	Kenyon, 1969
1937	1321	3302	9	Kenyon, 1969
1939	1355	3387	9	Kenyon, 1969
1943	3417	4556	12	Kenyon, 1969
1949	1087	1449	4	Kenyon, 1969
1959	1560	2080	6	Kenyon, 1969
1965	1144	1520	4	Kenyon, 1969
1968	2302	3940	10	Estes and Smith, 1973
1969	2354	4029	11	Estes and Smith, 1973
1970	2773	4746	13	Estes and Smith, 1973
1971	3241	5547	15	Estes and Smith, 1973
1972	4042	6432	17	Estes and Smith, 1973
Adak (257 km ² of habitat)				
1947*	0	0	0	Kenyon, 1969
1951	0	0	0	Kenyon, 1969
1952	0	0	0	Kenyon, 1969
1954	48	80	<1	Kenyon, 1969
1957	399	997	4	Kenyon, 1969
1959	1718	2291	9	Kenyon, 1969
1962	2260	3013	12	Kenyon, 1969
1965	1336	1781	7	Kenyon, 1969
1972	ND§	ND§	ND§	Personal observation

*These islands had sea otter populations prior to the period of unregulated hunting (1741–1911), especially where Aleut populations were small or absent (see Kenyon, 1969).

†ND, no data.

‡The increase of population estimates of sea otters at Amchitka after 1965 probably reflects improved survey technology and should not be construed as a real increase in abundance. (See Estes, Chap. 21, this volume, for details.)

§Although no counts or estimates were made, sea otter densities appeared to be similar to those observed at Amchitka in 1972.

lows of unequal levels per day). Low tides occur during daylight in spring and summer and at night in autumn and winter. The intertidal area has been divided into three regions: (1) supralittoral fringe, (2) midlittoral region (*Fucus*, *Hedophyllum*, and *Alaria* zones), and (3) sublittoral fringe (*Laminaria* zone) [see Lebednik and Palmisano (Chap. 17, this volume) for complete details]. The annual range of ocean temperature is 3 to 9°C, and salinity varies from 27 to 35 parts per thousand. The sea is ice-free year round. It is shrouded in fog during summer and stormy during all seasons.

Most of our studies were conducted on the southeast portion of the island. Intensive studies were made at Makarius Bay,* Rifle Range Point, and Duck Cove on the Pacific Ocean side and at Square Bay, Cyril Cove, Bat Island, Kirilof Point, Kirilof Rocks, Constantine Point, and Constantine Harbor on the Bering Sea side (Fig. 5).

Shemya, Attu, and Adak. We were unable to observe annual variations in biotic and nonbiotic

*Also known as St. Makarius Bay.

Fig. 2 - Map of Amchitka Island, Alaska.

Fig. 3—Wide intertidal rock bench at low tide south of Rifle Range Point on the Pacific Ocean coast of Amchitka Island, Alaska (Aug. 7, 1971).

Fig. 4—Narrow intertidal rock bench at low tide south of Square Bay on the Bering Sea coast of Amchitka Island, Alaska (Aug. 22, 1971).

Fig. 5—Map of southeastern portion of Amchitka Island, Alaska, showing study areas referred to in this chapter.

Fig. 6—Map of Shemya Island, Alaska, showing study areas referred to in this chapter.

factors at these islands because they were visited only once or twice for short periods of time. However, conditions observed at these islands (climate, water temperature, salinity, and seasonal development of invertebrate and algal communities) were comparable to those at Amchitka during similar times of the year.

Shemya is significantly smaller than the other three islands. A road adjacent to the shore circles the island and provides complete access to the shoreline. The Bering Sea side has a continuous sand beach. The Pacific Ocean side has a rocky shoreline composed mostly of boulders and cobble. There are well-developed benches on the northeast portion of the island at Bomb Point and Urchin Point (these names were assigned by the authors), which were the primary study areas (Fig. 6). The benches are similar to those at Amchitka except that they have more and larger tide pools.

Attu is larger than Amchitka. The intertidal area is generally inaccessible because of the lack of roads, and thus only a small portion of the eastern end of the island was visited (Fig. 7). Here the

intertidal area contained rock benches and cobble beaches similar to those at Amchitka. The well-developed bench at Massacre Bay was the primary study area (some gravel areas occurred on this bench). Murder Point and Chichagof Harbor were also studied.

Adak is similar to Attu in size, and its coastline is also generally inaccessible because of the lack of roads. Its many bays and harbors are protected from the open sea. Only a small portion of the northeastern corner of the island was visited (Fig. 8). Here the intertidal area is predominantly steep cobble beaches. There are also sand beaches and areas of large boulders. Adak does not have well-developed intertidal benches, although some narrow benches [10 to 15 m (33 to 50 ft) wide] at Kuluk Bay and at Cape Adagdak were studied. A large number of boulders and small sea stacks made the bench surface irregular. Because of these features and the vertical walls adjacent to the bench, Adak has more vertical space in the intertidal area than the other islands studied. Zeto Point, Finger Bay, the breakwater at Sweeper Cove, and Clam Lagoon were also studied.

Fig. 7—Map of Attu Island, Alaska, showing study areas referred to in this chapter.

METHODS

Rationale

Islands often may serve as natural experiments for testing biological hypotheses (Carlquist, 1965; MacArthur and Wilson, 1967; MacArthur, 1972). The advantage of this method is that certain variations among islands may be considered experimental treatments, and thus results can be obtained immediately. The disadvantage is that geographically isolated islands are allopatric; thus uncontrolled extraneous variation may creep into interpretations of results more than in well-controlled experiments.

The direct manipulation of sea otter population densities in the western Aleutian Islands (by introducing or removing animals) would have revealed their role in structuring nearshore communities. Such a study was not possible owing to resource and time limitations. We attempted, however, to determine the role of the sea otter indirectly by (1) comparing nearshore communities of nearby islands similar in most respects except for sea otter densities; (2) comparing in time

nearshore communities at islands where sea otter densities have recently undergone large changes (Amchitka and Adak); and (3) observing, manipulating, and experimenting with organisms (primarily invertebrates and kelp) that we suspected of being affected by sea otter predation.

Sea otters have been near equilibrium density in the Rat Island group of the Aleutian archipelago (Fig. 1) for about the last 20 to 30 years, following almost complete annihilation by Russian and American fur traders during the eighteenth and nineteenth centuries (Kenyon, 1969; Estes, Chap. 21, this volume). Conversely, the sea otter population has not reestablished itself in the Near Islands (Fig. 1). The once abundant sea otter population there also was extirpated by over-exploitation, but immigrants from the densely populated Rat Islands were unable to reach the Near Islands, which are approximately 330 km (200 miles) to the west northwest of Amchitka and are separated from the Rat Islands by wide deep oceanic passes. Since 1959 there have been scattered reports of sea otters in the Near Islands (Kenyon, 1969), although no major population

Fig. 8—Map of Adak Island, Alaska, showing study areas referred to in this chapter.

reestablishment has occurred. Thus the presence and absence of sea otters in the Rat and Near Islands, respectively, serve as our natural experiment. After careful consideration and consultation, we believe that other factors, such as climate and tides, which are capable of dynamically influencing nearshore marine community structure, are sufficiently similar between the two island groups that they need not be seriously considered, and thus we should be able to determine the actual effect of sea otter predation on the nearshore community simply by comparing the Rat and Near Islands.

Intertidal Community

Most of our observations were restricted to the midlittoral area [$+0.8$ to 0 m ($+2.6$ to 0 ft)] and sublittoral fringe [0 to -0.7 m (0 to -2.3 ft)] of rock benches because these areas provided the greatest biotic diversity (Weinmann, 1969; O'Clair, Chap. 18, this volume).

We determined the size and density of plants and animals either by removing all materials from

inside $\frac{1}{16}$ -, $\frac{1}{4}$ -, or 1 -m² sample frames and returning them to our laboratory for measurements or by measuring these parameters in situ. Sample plots were selected by tossing a frame arbitrarily into selected algal associations and by placing a frame at random intervals along either side of a random transect which was perpendicular to shore and which transversed the entire association of intertidal algae (O'Clair and Chew, 1971). Food habits of intertidal invertebrates were determined by observing feeding animals or by examining gut contents of collected animals. We collected additional information during "beach walks" along many kilometers of shoreland during daylight low tides.

Grazing Studies. To test the effect of sea urchin grazing on intertidal algae at Amchitka (i.e., to simulate low sea otter densities), we placed twenty 19-mm-diameter sea urchins (*Strongylocentrotus polyacanthus*) from the subtidal area at Constantine Harbor (Fig. 5) in each of four 0.5 -m² plastic (Vexar) mesh cages (mesh,

3 by 4 mm) with aluminum mesh tops (mesh, 13 by 13 mm). Two cages were permanently secured (nailed) in areas with a canopy of either 100% *Laminaria longipes* or *Hedophyllum sessile* in Makarius Bay (Fig. 5) in September 1971. A control cage without sea urchins was also provided for each algal type, and the percentage of algal cover in all cages was recorded bimonthly from December 1971 to June 1972.

To determine the development of marine algae at Shemya in the absence of grazing by sea urchins (i.e., to simulate high sea otter densities), in September 1971 we removed all sea urchins from two tide pools (6 by 3.3 by 1.5 m and 3.5 by 1 by 0.8 m) that contained only coralline algae and *Thalassiophyllum clathrus*. Two adjacent tide pools with sea urchins were selected as controls. In July 1973 the species and percentage of cover of algae and the number of sea urchins were recorded for all four tide pools.

We studied the effect of limpets (*Collisella pelta*) grazing on intertidal algae by using fifteen 133-cm² bottomless plastic dog dishes (Dayton, 1970) with aluminum mesh tops as inclusion and exclusion cages. Three cages each were secured in 1-m² areas that had recently been denuded of *L. longipes*, *H. sessile*, and *Halosaccion glandiforme* at Makarius Bay and of *Corallina vancouveriensis* and *Alaria crispa* at Duck Cove (Fig. 5) in July 1971. Two cages in each area contained three 30-mm-long limpets, and the third cage served as a control. Two weeks before the experiment, the study areas were cleared of plants and animals with a shovel, putty knife, and wire brush and by burning twice with a 1 : 1 mixture of fuel oil and unleaded gas. Species composition and the percentage of cover of algae in all dishes were recorded bimonthly until August 1973.

We selected four areas (50 to 150 cm²) of bare rock in the midlittoral region at Makarius Bay, each of which contained one or two limpets (20 to 40 mm long). Each area was marked with a nail and rope. Beginning in July 1971, limpets were removed and subsequently kept from two areas, and the other two areas served as controls. Algal cover was recorded bimonthly in all four areas until August 1973.

Because the dense standing crop of algae at Amchitka is not noticeably grazed by epibenthic herbivores, we wondered if this abundant resource is used by other herbivores after it is dislodged from the substrate. To determine if drift kelp would be eaten by small intertidal crustaceans (amphipods and isopods), we collected and cut into 1-cm² pieces *L. longipes*, *H. sessile*, *A. crispa*, and *A. fistulosa*. Six pieces of each alga were placed in 240-ml cups containing either filtered

fresh seawater, seawater and four isopods (*Idotea wosnessenskii*), or seawater and four amphipods (*Parallorchestes ochotensis*). The 12 cups were kept outdoors and were observed several times a day. The water was changed after each observation, and the condition of the algae was recorded. This experiment proceeded for 2 days and was then repeated with another group of similar plants and animals.

Growth and Feeding Studies. The small diameter of sea urchins in the intertidal area at Amchitka could be due to extensive predation or to genetic limitation. To determine which factor is most important, in May 1971 we transported five sea urchins ($\bar{x}$, 15.2 mm in diameter) to the marine laboratories at Friday Harbor, Washington, and placed them in a permanently filled continuous-flow seawater table. Water temperature ranged from 4 to 15°C during the experimental period. The water table was periodically supplied with brown algae, mostly *Nereocystis luetkeana* and *Costaria costata*. The diameters of the sea urchins were measured bimonthly. This growth experiment was terminated in June 1972 after all five sea urchins had died, apparently because of low dissolved oxygen and low salinity.

Intertidal sea stars and snails prey on barnacles and mussels (Connell, 1972; Spight, 1972). The small size of these predators on the benches at Amchitka may be due to low densities of barnacles and mussels or to genetic limitations. To test this, in May 1971 we transported 20 sea stars [*Lepasterias alaskensis* ($\bar{x}$, 14.9-mm arm radius; $\bar{x}$, 1.5 g live weight)] to Friday Harbor. Their water table was periodically supplied with opened live clams (*Protothaca staminea*), mussels (*Mytilus edulis*) (4 to 8 cm long), and live barnacles (*Balanus glandula*). The weight and arm radius were determined bimonthly until all 20 sea stars died (June 1972). Twenty predacious snails (*Thais lima*; $\bar{x}$, 18 mm total length) were transported from the benches at Amchitka to the Department of Zoology, University of Washington, in July 1971 where they were placed in liter beakers containing seawater and several live barnacles (*B. glandula*) at a controlled temperature of 10°C. This experiment was terminated after 1 month (R. T. Paine, personal communication).

Mussel (*M. edulis*) densities may be low at Amchitka because of predation or inadequate food. To determine this, in April 1972 we transported about 50 subtidal mussels (*M. edulis*; $\bar{x}$, 17 mm long) from Puget Sound to Amchitka. Twelve mussels were placed on each of three 1-cm-diameter polyethylene ropes, and four mussels were placed in each of three 700-ml perforated

polyurethane bottles. The ropes and bottles were suspended from the dock in Constantine Harbor with the mussels just below the water surface at the -0.7-m (-2.3-ft) tidal level. The mussels were measured every four months until August 1973.

Selective grazing by sea urchins on a competitively dominant intertidal alga could affect community composition by reducing competition for space and thus permitting more algal species to coexist. To determine if sea urchins at Amchitka feed selectively, at Constantine Harbor we conducted food-preference tests in a 1.5-m (5-ft)-diameter by 30-cm (12-in.)-deep plastic wading pool supplied with constantly flowing fresh seawater. A weighted wooden "Y" maze divided the pool into three equal sections. Five 19-mm-diameter sea urchins from the intertidal area at Amchitka were placed in one branch of the maze; *T. clathrus* (a subtidal kelp) was placed in another; and either *L. longipes*, *A. crispa*, or *H. sessile* (all lower intertidal kelp) was placed in the third. *Thalassiophyllum clathrus* was used in all tests, and one of the other three kelps was used during two consecutive days. Fresh kelp was provided daily. At 0800 and 2000 each day, the location and activity of each sea urchin was recorded. The sea urchins were replaced to their original location (twice daily), and the position of the two kelp species was exchanged. Each test ran for six consecutive days and then was repeated with five different sea urchins. Two similar tests were carried out at Amchitka with two groups of 75-mm-diameter sea urchins from the intertidal region at Shemya.

Siltation Studies. Silt accumulates in protected areas and is capable of smothering barnacles and mussels. We conducted experiments at Amchitka to determine the intertidal areas of silt accumulation and the effects of siltation on mussel survival.

To determine areas of silt accumulation in the intertidal region, we nailed two plastic dishpans [10 cm (4 in.) high and 560 cm² in area] in each of the same five 1-m² denuded areas used in the limpet grazing experiments. These pans were placed over areas that contained 100% cover of young algae (either *Ulva lactuca*, *Fucus distichus*, *H. glandiforme*, *H. sessile*, or *A. crispa*) in July 1972. For water movement and light penetration, the pan tops were removed and four equally spaced 4- by 2-cm openings were placed 2 cm above the bottom. The areas covered by the pans were examined periodically until the pans were removed in August 1973.

On Dec. 15, 1972, we placed two groups of 15 mussels (*M. edulis*, 20 to 60 mm long) each from

the subtidal region in Puget Sound in secured dog dishes in the *Laminaria* and *Halosaccion* zones at Makarius Bay to test the effects of siltation on mussel survival. The mussels appeared to be attached to the substratum when the dishes were removed on Dec. 19, 1972. The condition of the mussels was observed in April and August 1973.

Settling Studies. The absence of appreciable barnacle (*Balanus* spp.) and mussel (*M. edulis*) sets on the benches at Amchitka may be due to the absence of larvae or to the absence of available substrate. To determine if barnacle or mussel larvae would set if space were provided, in December 1971 we nailed one each of five 1-m-long stainless-steel wires, each holding five 15-cm (6-in.)-long oyster shell halves (*Crassostrea gigas*) from Puget Sound, in the same five 1-m² denuded areas used in the limpet grazing studies. The shells as well as the denuded rock areas were checked bimonthly until August 1973 for settling animals.

Determination of Wave Exposure. Because we believe that the degree of exposure affects community structure, we wanted an independent quantitative measure that would enable us to compare the relative exposure of our study locations. Weinmann (1968) observed that the width of *L. longipes* blades reflected relative exposure (blades were wide in protected areas and narrow in exposed areas). Therefore we used the blade width of this kelp as an indicator of exposure.

Subtidal Community

Subtidal communities were observed at Attu and Shemya Islands in the Near Island group, at Amchitka Island in the Rat Island group, and at Adak Island in the Andreanof Island group. Qualitative observations over wider areas in these islands indicate that our study areas are representative of respective island groups.

Time limitations and logistic problems allowed only a single dive* on June 21, 1972, at Murder Point, Attu Island (Fig. 7). We also made nine dives during August and September 1971 and June 1972 at three different locations along the coast at Shemya Island. All these study areas were chosen primarily because of accessibility in view of the limited time available for work in the Near Islands.

We studied four subtidal areas at Amchitka between March 1971 and September 1972. Forty-six dives were made during the observation period.* All study areas were selected from the Bering Sea side of Amchitka Island for the following reasons:

*Refers to number of dives made by a "dive team."

1. The Bering Sea was logistically more convenient because support facilities were located at Constantine Harbor (Fig. 5).

2. Weather conditions are generally more favorable on the Bering Sea than on the Pacific Ocean. Prevailing westerly winds cause the Pacific Ocean to be rough, whereas the Bering Sea is comparatively more calm.

3. The underwater slope is steeper along the Bering Sea coast than it is along the Pacific Ocean coast of Amchitka (see the Geological Survey map in the pocket at the back of this volume); thus a diver can observe a relatively greater depth range without excessive swimming or boat work.

4. Several dives made in the Pacific Ocean in the vicinity of Makarius Bay (Fig. 5) confirm that the community structure in the Pacific Ocean is qualitatively similar to that in the Bering Sea.

Bat Island and Kirilof Rocks (Fig. 5) are heavily exposed during storms off the Bering Sea. Constantine Point is protected from the direct force of storm surf and is apparently only moderately exposed. Kirilof Point is well protected from heavy seas by Kirilof Rocks and the confines of Constantine Harbor. Our observations of the rocky subtidal communities at Amchitka therefore are more extensive and from a wider range of exposure of subtidal communities than at the Near Islands.

We observed depths of subtidal epibenthic communities to 25 m (80 ft) in the Near Islands and to about 40 m (130 ft) at Amchitka.*

The percentage of cover and vertical distribution of the following epibenthic algal groups and species were documented.

1. *Laminaria longipes*.

2. The digitate *Laminaria* life form. This includes *L. groenlandica*, *L. dentigera*, and *L. yezoensis*.

3. *Agarum cribrosum*.

4. *Thalassiophyllum clathrus*.

5. *Desmarestia* sp.

6. Foliose Rhodophyta.

7. Total macrophytic vegetation—The predominantly subtidal (digitate) species of *Laminaria* were grouped because they are not individually recognizable except on close examination. Although *L. yezoensis* is identifiable on close in situ examination, *L. groenlandica* and *L. dentigera* require stipe section for species identification (Druehl, 1968). Otherwise each of the preceding species or groups of species is easily recognized. Together these species contribute most of the

biomass to the epibenthic macrophyte association in the subtidal area of the western Aleutian Islands.

We estimated the coverage of each species or species group at 3-m (10-ft) depth intervals, beginning at a depth of 3 m (10 ft) and starting from a point arbitrarily selected along the shore. Vegetation coverage was estimated to a depth of about 27 m (90 ft) (when possible), at which point the divers swam parallel to the shore for a sufficient distance to avoid overlap with the area observed during descent. They then made similar coverage estimates during ascent.

When depths to coverage estimates were assigned, tidal fluctuations were not considered. Water depth was determined by a standard oil-filled depth gage, which is probably not accurate to more than a few meters. Tidal fluctuations at Amchitka are not great. The tidal range is 1.2 m (4 ft) at Sweeper Cove on Adak Island (Coast and Geodetic Survey, 1968), and the tidal range at Amchitka Island is close to this value.

Data on vegetation coverage were transformed to Arcsin square-root percent values to approximate a normal distribution (Ostle, 1963). The mean, standard deviation, and 95% confidence interval were calculated within the transformation for each species or species group at each depth for data collected at Kirilof Point. The calculations then were retransformed to percentages from Arcsin square-root percent values. Only the means were determined for data collected at the remaining three study areas because of small sample sizes at each depth.

Sea urchin (*S. polyacanthus*) densities and size class distributions were estimated according to the technique described by Barr (1971). Briefly this involves random placement of a 0.25-m² quadrat on the ocean floor and counting the number of sea urchins within a quadrat. The animals were taken to the laboratory where their test diameters were measured. The data used to estimate size class distributions and the maximum density of sea urchins at Amchitka are from Barr (1971). Additionally, we measured sea urchin densities at 3-m depth intervals between the depths of 3 and 20 m (10 and 66 ft) at each of the four Amchitka study areas and at depths of 3, 10, and 25 m (10, 33, and 82 ft) at Shemya Island.

Sea urchin wet weight (blotted dry) and test diameter were measured from 110 individuals throughout the naturally occurring size spectrum at Shemya and Attu. We fit the linear model $y_i = \mu + \beta(x_{ij}) + e_{ij}$ to the data by the method of least squares, where y is the log sea urchin mass in grams, x is the log sea urchin diameter in millimeters, μ is -7.875 , and β is 2.992 . A correlation

*Although at Amchitka we dived to 40 m (130 ft) on one occasion, most work was conducted between the surface and 27 m (90 ft).

Fig. 9—Diagram of the interactions within nearshore communities with and without sea otter populations. See Discussion for complete details.

coefficient of 0.992 indicates a very good linear fit of the log-log transformation. Parametric interval estimates and tests of hypothesis are given in the appendix. The variance of (e) is quite small, and therefore simple least-squares estimators of μ and β are rather precise. With the use of this model as our estimator, biomass was superimposed on each size class distribution of sea urchins.

DESCRIPTION OF COMMUNITIES

Community Differences

The most prominent biological features of the marine community studied at Amchitka are the extensive little grazed subtidal and intertidal beds of marine algae and the sparse population of certain benthic invertebrates (Table 1). In contrast, the prominent biological features of the marine communities studied at Attu and Shemya are the sparse heavily grazed offshore and intertidal beds of marine algae and the dense population of large benthic invertebrates (Table 1). The marked decline in the population and size of sea urchins that occurred concurrently with an increase in the population of sea otters at Adak and Amchitka during the previous 15 years (Kenyon, 1969) suggests that sea otter predation has been the

principal factor responsible for altering the composition of these marine communities (Fig. 9). Furthermore, the contents of Aleut kitchen middens at Amchitka indicate that sea urchins were larger centuries ago than today (Desautels et al., 1970) when, Kenyon (1969) speculates, there were fewer sea otters because of intensive native hunting pressure. That Desautels also found sea otter bones in these middens supports this speculation.

Intertidal Communities

Amchitka. A complete mat of virtually ungrazed algae occupies intertidal benches, channels, and tide pools at Amchitka (Fig. 10). *Laminaria longipes* completely covers the lowest portion of the intertidal region (sublittoral fringe). *Hedophyllum sessile* predominates in the lower midlittoral region in protected areas and on the landward side of wide benches. *Alaria crispa* occupies this portion of the lower midlittoral region in exposed areas and on narrow benches. *Halosaccion glandiforme*, *Iridaea cornucopiae*, and *Fucus distichus* cover the higher zones of the midlittoral region (see Lebednik and Palmisano, Chap. 17, this volume).

There is little evidence of grazing on larger plants in the kelp communities at Amchitka.

Fig. 10—Continuous mat of virtually ungrazed algae on intertidal rock benches at Amchitka Island, Alaska, at low tide (Aug. 7, 1971).

Grazed kelp is recognized by its serrated edges. This characteristic mark made by sea urchins and other benthic herbivores, such as chitons, was noticed in less than 1% of the attached kelp examined. Over 39% of young kelp [under 20 cm (8 in.) long] were grazed (Table 3); however, the size of the serrations and the abundance of small amphipods and isopods suggest that these small crustaceans may have grazed the smaller kelps.

Invertebrates are inconspicuous on the intertidal benches at Amchitka (Fig. 10). Barnacles (*Balanus glandula* and *B. cariosus*) and mussels (*Mytilus edulis*) (sessile filter-feeding invertebrates) and sea urchins (*S. polyacanthus*), chitons (*Katharina tunicata*), and limpets (*C. pelta*) (motile herbivorous invertebrates) are small and scarce (Tables 4 and 5). Some invertebrates (barnacles, limpets, and snails) are covered by silt or overgrown by algae in areas protected from wave action. Even the most abundant invertebrates [polychaetes, certain crustaceans (amphipods and isopods), sea anemones, sea cucumbers, and mollusks (clams and snails)] are inconspicuous because of their small size and occurrence under algal mats, in algal holdfasts, under rocks, and on the bottoms of pools and channels. Only small littorine snails in the mid and upper intertidal areas are conspicuous. Therefore in most areas intertidal algae appeared to be the sole inhabitants of the intertidal bench (a more complete description of intertidal inverte-

brates is given by O'Clair in Chap. 18, this volume). However, sessile filter-feeding invertebrates (barnacles and mussels) are more abundant in areas exposed to a higher degree of wave action, e.g., Banjo Point (Fig. 5), than in protected locations, e.g., Makarius Bay (Table 4).

No sea urchins were observed grazing intact vegetation on the bench, in channels (Fig. 11), or in tide pools. However, sea urchins did graze algal debris and detritus in these locations. Sea urchin guts contained macrophytic algae and diatoms.

Adak. Although the algal community of Adak covers the intertidal rock bench and is ungrazed, it is not as extensive as the one at Amchitka. The majority of the community is composed of *L. longipes* and *A. crispa*. *Hedophyllum sessile* is not abundant. *Thalassiophyllum clathrus* and *Cymathere triplicata*, normally subtidal kelp at Amchitka, are present in the intertidal area at Kuluk Bay.

At Adak, as well as at Amchitka, the invertebrates on the rock bench are small, scarce, and inconspicuous. There are, however, extensive mussel (*M. edulis*) beds and dense populations of barnacles (*B. glandula* and *B. cariosus*) on vertical walls, on sea stacks, and on the sides of large boulders. Dense populations of large predacious snails (*Thais lima*) were observed feeding in these areas (Table 6). The breakwater protecting

Table 3—Percentage of Intertidal Random Individual Kelp Plants Grazed and Random 0.25-m² Quadrats Containing Grazed Kelp, Amchitka and Shemya Islands, Alaska, 1971–1973

Item	Amchitka				Shemya			
	Sample size	Bench	Tide pools	Channels	Sample size	Bench	Tide pools	Channels
Random plants								
<i>Laminaria longipes</i>								
>200 mm long	16,000	<1	<1	<1	1600	ND*	100†	100†
<i>Alaria crispa</i>								
>200 mm long	3,000	<1	<1	<1	140	ND	100†	100†
<200 mm long	117	49.6	ND	ND	ND	ND	ND	ND
<i>Hedophyllum sessile</i>								
>200 mm long	4,200	<1	<1	<1	310	ND	100†	100†
<200 mm long	2,351	38.4	ND	ND	ND	ND	ND	ND
Random 0.25-m ² quadrats								
<i>Laminaria longipes</i>	400	<1	<1	<1	40	80	100†	100†
<i>Alaria crispa</i>	400	<1	<1	<1	20	80	100†	100†
<i>Hedophyllum sessile</i>	400	<1	<1	<1	30	75	100†	100†

*ND, no data.

†All three species of kelp were absent from channels and tide pools, and all those overhanging these areas were grazed.

Table 4—Mean Numbers Per Square Meter of Selected Intertidal Invertebrates at Amchitka and Shemya Islands, Alaska, 1968–1973*

Invertebrate	Amchitka			Shemya‡		
	Makarius Bay	Banjo Point	All areas†	Bench	Tide-pool walls	Channel bottom
Sea urchin						
(<i>Strongylocentrotus polyacanthus</i>)	8	4	8	78	139	231
Limpet						
(<i>Collisella pelta</i>)	2	127	8	356	82	ND
Chiton						
(<i>Katharina tunicata</i>)	<1	<1	<1	38	ND	ND
Barnacles						
(<i>Balanus glandula</i>)	<1	114	6	2242	ND	ND
(<i>B. cariosus</i>)	<1	82	4	188	ND	ND
Mussel						
(<i>Mytilus edulis</i>)	<1	36	4	722	ND	ND
Snail						
(<i>Thais lima</i>)	2	3	3	32	ND	ND
Hermit crab						
(<i>Pagurus hirsutiusculus</i>)	<1	<1	<1	20	ND	ND

*Preliminary data from transect-line $\frac{1}{16}$ -m² plots [Amchitka, N = 32; Shemya, N = 23 (O'Clair, in preparation)] and from randomly selected $\frac{1}{4}$ -m² plots [Amchitka, N = 171; Shemya, N = 9 (see Estes and Palmisano, 1974)].

†Rifle Range Point, Duck Cove, Makarius Bay, and Banjo Point.

‡Urchin Point.

Sweeper Cove contained a dense population of sea urchins, (*S. polyacanthus*) among the large boulders (Table 5). This is the only area along the shore where live sea urchins were seen. Hermit crabs (*Pagurus* sp.) also occur at Adak. Mussels, clams (*Protothaca* sp.), and cockles (*Clinocardium nuttalli*) were observed in Clam Lagoon.

Shemya. Algae are heavily grazed in the lower intertidal area (Fig. 12), in channels (Fig. 13), and in tide pools (Fig. 14) at Shemya, and there is a definite browse line at the low water level (Fig. 12). Channels and tide pools beneath the low water level are devoid of most species of algae. *Laminaria longipes* does not form a complete mat

Table 5—Sizes of Selected Invertebrate Herbivores from the Western Aleutian Islands*

Area	$\bar{x}$	R	N	SD	CI
Sea urchins					
Amchitka					
Intertidal bench	18.9	4 to 45†	224	5.7	±11.2
Subtidal area					
Constantine Dock‡	30.9	17 to 56	345	6.7	±13.1
10 to 20 m§	16.5	3 to 34	872	5.8	±11.4
45 to 80 m¶	41.1	26 to 80	207	10.4	±20.4
Shemya					
Intertidal bench	30.4	4 to 74	289	17.9	±35.1
<i>Hedophyllum</i> zone	22.8	4 to 70	153	16.0	±31.4
<i>Laminaria</i> zone	37.6	10 to 74	136	16.8	±32.9
Tide-pool walls	52.2	25 to 70	130	7.7	±15.1
Channel bottom	53.4	22 to 81	140	17.4	±34.1
Attu					
Intertidal bench	52.8	28 to 99	14	ND	ND
Channel bottom	87.5	78 to 108	13	ND	ND
Adak					
Breakwater**	28.4	10 to 50	121	8.6	±16.9
Growth experiment††					
May 1971	15.2	12 to 18	5	2.4	±6.7
May 1972	36.2	34 to 38	5	2.0	±5.6
Midden remains‡‡	69.7	21 to 106	1403	9.8	±19.2
Limpets					
Amchitka					
Intertidal bench	27.8	18 to 51	60	1.8	±3.6
Adak					
Intertidal bench	25.1	10 to 42	75	1.5	±2.9
Shemya					
Tide-pool walls	ND	19 to 67	200	ND	ND
Chitons					
Shemya					
Intertidal bench	67.2	23 to 88	77	18.1	±36.0

* $\bar{x}$, average individual size in millimeters (test diameter for sea urchins, total length of longest axis for others); R, range of individual sizes in millimeters; N, number of animals measured; SD, standard deviation; CI, 95% confidence interval; ND, no data.

†Only six sea urchins were larger than 29 mm in diameter.

‡Collected beneath dock with scuba [5 to 6 m (16 to 20 ft) deep].

§Barr, 1971.

¶Collected 45, 50, and 80 m (148, 164, and 262 ft) deep by bottom dredge.

**Collected at low tide between the rocks of the Sweeper Cove breakwater.

††Amchitka intertidal sea urchins fed at Friday Harbor Laboratories for 1 year.

‡‡Desautels et al., 1970.

in the sublittoral fringe. Instead there are areas of only *L. longipes* stipes and holdfasts or of bare rock and areas containing *T. clathrus* and *L. groenlandica*. (*T. clathrus* and *L. groenlandica* occur only subtidally or in tide pools on Amchitka.) *Hedophyllum sessile* is heavily grazed in the lower midlittoral region and is absent or heavily grazed in channels and tide pools. The upper midlittoral region and the landward end of the bench contain *H. glandiforme*, *I. cornucopiae*, and *F. distichus* and are not heavily grazed. *Thalassiphyllum clathrus*

occupies areas of several square meters in this zone (Fig. 15). All *L. longipes*, *A. crista*, and *H. sessile* overhanging channels are grazed. Eighty percent of all 0.25-m² *L. longipes* plots and 75% of all *H. sessile* plots sampled contained grazed plants (Table 3). The only plants not heavily grazed were coralline algae and *T. clathrus*, which are usually present in channels, tide pools, and the lower intertidal areas.

Dense populations of large sea urchins (*S. polyacanthus*) (Fig. 16) and large chitons (*K.*

Fig. 11—Ungrazed *Laminaria longipes* on wall and bottom of an intertidal channel at Amchitka Island, Alaska, at low tide (Aug. 7, 1971).

Table 6 - Sizes of Intertidal Predacious Sea Stars and Snails in the Western Aleutian Islands*

Area	$\bar{x}$	R	Size			Weight				
			N	SD	CI	$\bar{x}$	R	N	SD	CI
<i>Leptasterias alaskensis</i>										
Amchitka	14.9	3 to 44	1144	6.0	± 11.8	1.5	0.1 to 13.6	571	1.5	± 2.9
Shemya	25.6	6 to 55	41	11.3	± 22.7	5.3	0.1 to 25.8	33	4.2	± 8.6
Growth experiment†										
May 1971	15.4	5 to 26	20	5.6	± 11.7	1.3	0.2 to 3.5	20	1.7	± 3.6
May 1972	26.9	12 to 49	20	13.5	± 28.2	5.9	0.9 to 18.3	20	5.0	± 10.5
<i>Thais lima</i>										
Amchitka										
Intertidal	20.9	10 to 35	98	8.5	± 16.9					
Makarius Bay	18.1	15 to 20	8	2.0	± 4.7					
Duck Cove	17.2	10 to 27	57	6.9	± 13.8					
Banjo Point	29.6	25 to 35	23	8.0	± 16.5					
Constantine Harbor	24.1	14 to 31	10	5.2	± 11.8					
Adak										
Kuluk Bay	22.6	11 to 40	330	8.0	± 15.7					
Attu										
Chichagof Harbor	42.8	34 to 50	10	6.8	± 15.4					

* $\bar{x}$, average individual size in millimeters (arm radius for sea stars, total length of shell for snails) or live weight in grams; R, range of individual sizes in millimeters or live weight in grams; N, number of animals measured; SD, standard deviation; CI, 95% confidence interval.

†Amchitka intertidal sea stars fed at Friday Harbor Laboratories for 1 year.

Fig. 12—Heavily grazed algae on intertidal rock benches at Shemya Island, Alaska, at low tide. Note sea urchins in foreground and barnacles (white) in background (Sept. 2, 1971).

Fig. 13—Grazed *Laminaria longipes* on wall and bottom of an intertidal channel at Shemya Island, Alaska, at low tide. Note density of sea urchins in channel (Sept. 2, 1971).

Fig. 14—Tide-pool wall and bottom devoid of algae at Shemya Island, Alaska, at low tide. Note sea urchins beneath water surface and limpets (white ovals) on tide-pool wall (Sept. 2, 1971).

Fig. 15—Large area of *Thalassiophyllum clathrus* in *Laminaria* zone at Shemya Island, Alaska, at low tide (June 29, 1972).

Fig. 16—Dense concentrations of large ($\bar{x}$, about 70 mm in diameter) sea urchins in lower intertidal zone at Shemya Island, Alaska, at low tide. Note large sea star (arm radius, 55 mm) to right of center (Sept. 2, 1971).

tunicata) and extensive beds of mussels (*M. edulis*) and barnacles (*B. glandula* and *B. cariosus*) (Table 4) occur on the intertidal benches at Shemya. Sea urchin density and size are greater in channels and tide pools than in the lower and higher intertidal regions (Tables 4 and 5). Chitons are present only in the *Hedophyllum* and *Laminaria* zones. *Balanus glandula* is most abundant in the upper midlittoral region (Fig. 12), but *B. cariosus* is most abundant in the sublittoral fringe and lower midlittoral region where it occurs with *L. longipes* (Fig. 17) and *H. sessile*. Mussel beds are most abundant on the seaward edge of the bench in the high midlittoral region. Predacious sea stars (*Leptasterias alaskensis*) are larger here than at Amchitka (Table 6). Hermit crabs (*Pagurus* sp.) are abundant on the bench, in tide pools, and in channels in the upper midlittoral region. Amphipods and isopods are not as abundant here as at Amchitka. Fewer than 20 individual amphipods and isopods were present under small rocks at low tide. Limpets (*C. pelta*) are large and abundant on tide-pool walls and in the lower intertidal area (Tables 4 and 5 and Fig. 14).

Sea urchins were observed grazing primarily *L. longipes*, *H. sessile*, *A. crispa*, and *Ulva* sp. Only rarely were they observed grazing *T. clathrus*. Gut

analyses of over 100 sea urchins (range of 10 to 75 mm in diameter) showed that kelp was most abundant followed by *Ulva* sp. and diatoms. *Leptasterias alaskensis* and *T. lima* were observed preying on mussels and barnacles. One *L. alaskensis* was observed scavenging a sea urchin.

Attu. The algal association at Attu is heavily grazed in the lower intertidal area, in channels, and in tide pools and is very similar to the association at Shemya. *Thalassiophyllum clathrus* occurs in the lower intertidal area, in tide pools, and in channels and is virtually ungrazed.

The invertebrate association at Attu also is similar to the association at Shemya. Dense populations of sea urchins (*S. polyacanthus*), chitons (*K. tunicata*), mussels (*M. edulis*), and barnacles (*B. glandula* and *B. cariosus*) occur on the bench. Densities of hermit crabs (*Pagurus* sp.) and crustaceans (amphipods and isopods) also are similar to those at Shemya. Littleneck clams (*Protothaca* sp.) occur in gravel beds in the midlittoral region, and the large chiton (*Cryptochiton stelleri*) was noticed in the sublittoral fringe.

The food habits of sea urchins and predacious sea stars and snails were similar to those at Shemya.

Fig. 17 —Abundant *Balanus cariosus* in *Laminaria* zone at Shemya Island, Alaska, at low tide [ruler is 30.5 cm (12 in.) long] (June 28, 1972).

Sea urchins at Massacre Bay and Murder Point on Attu are larger than those at Shemya (Table 5). Sea urchins in Chichagof Harbor appeared to be smaller (although no measurements were made) than those at the other two study areas at Attu.

Subtidal Communities

Amchitka and Adak. The subtidal macrophytic association at Amchitka extends from the intertidal area and covers most of the solid-rock substrate to depths of 20 to 25 m (66 to 82 ft) (Figs. 18 to 20). Major contributors to this association are *Alaria fistulosa*, *Laminaria longipes*, *L. groenlandica*, *L. yezoensis*, *L. dentigera*, *Agarum cribrosum*, *Thalassiophyllum clathrus*, *Desmarestia* sp., and various Rhodophyta. *Laminaria* and *Agarum* are the most abundant forms.

Sea urchin population densities increase with increasing depth at Amchitka (Fig. 19). At the sublittoral fringe, sea urchins are seen infrequently unless they are associated with algal holdfasts or protective cracks and crevices in the substrate. Openly exposed sea urchins are rarely seen in water shallower than 10 m (33 ft). Below about 15 to 20 m (50 to 66 ft), high-density sea urchin populations are openly exposed in some areas.

Phillip A. Lebednik (personal communication) reported that the rocky subtidal community (algal associations and sea urchin size, density, and

distribution) at Adak appears to be comparable to that at Amchitka. He made only a single dive at Adak in 1972 [at 7, 13, 20, 27, and 34 m (23, 43, 66, 89, and 112 ft) depths], but he made 62 dives at Amchitka and 4 dives at Shemya.

Shemya and Attu. Subtidal macrophytes are generally absent from solid-rock substrate in the Near Islands (Figs. 19 and 21). They occur only in small isolated patches, frequently located on submarine pinnacles, and often in a state of destruction from sea urchin grazing.

Sea urchin densities at Shemya and Attu decrease with increasing water depth (Fig. 19). Immediately below mean water level, sea urchin populations frequently completely cover the entire rocky substrate.

Vegetation. No data on vegetation coverage were collected at the Near Islands. Subtidal macrophytes are absent from most areas at the Near Islands, and thus a coverage of zero percent is inferred from our general observations (Fig. 19).

At Amchitka *L. longipes* extends from the sublittoral fringe to a depth of 3 to 10 m (10 to 33 ft). This species possesses a stipe that allows it flexibility in an area where wave action is maximum. The association of three species (*L. groenlandica*, *L. yezoensis*, and *L. dentigera*) begins at mean water level and extends out to a depth of

Fig. 18.—Vegetation coverage as a function of depth at the four Amchitka Island, Alaska, study areas.

Fig. 19—Total macrophyte coverage and sea urchin density as a function of depth at Amchitka and Shemya Islands, Alaska.

Fig. 20—Dense ungrazed subtidal kelp beds in nearshore community of Amchitka Island, Alaska (*Laminaria longipes* in foreground and *Alaria fistulosa* in background) (Aug. 5, 1972).

Fig. 21—Nearshore community of Shemya Island, Alaska, showing a virtually complete absence of subtidal kelp. Note light-colored rock bottom (June 30, 1972).

23 to 25 m (75 to 82 ft). This association of species is dominant between about 3 and 12 m (10 and 40 ft). *Agarum cribrosum*, which begins at a depth of about 6 m (20 ft) and extends out to a depth of at least 23 to 25 m (75 to 82 ft), is most abundant between 16 and 20 m (52 and 66 ft). *Thalassiphyllum clathrus* and *Desmarestia* sp. are only relatively minor contributors to the sublittoral macrophyte association and seldom cover more than 10% of the rocky substrate. *Thalassiphyllum clathrus* ranges in depth between 3 and 20 m (10 and 66 ft) and is most abundant at a depth of about 10 to 12 m (33 to 40 ft). *Desmarestia* sp. also ranges in depth between 3 and 20 m (10 and 66 ft) but shows no distinct pattern of maximum abundance. Foliose Rhodophyta occur from the sublittoral fringe to beyond 25 m (82 ft) in depth. Near the surface Rhodophyta grow beneath the *Laminaria* canopy as well as epiphytically on the Phaeophyta. Abundant space is available on the rock substrate in the shallow subtidal region because blades of *L. groenlandica*, *L. dentigera*, and *L. yezoensis* are extended a meter or more toward the surface on thick inflexible stipes. Rhodophyta are abundant continuously from the surface to beyond 25 m (82 ft), perhaps showing a slight increase in abundance with increased depth (see Chap. 17, this volume, for distribution of *A. fistulosa*).

Sea Urchin Populations. The size class distribution of a typical high-density sea urchin

population at Amchitka is shown in Fig. 22a. These data indicate that the maximum test diameter of subtidal sea urchins at Amchitka Island is about 35 mm. Biomass distribution (as a function of size class) is also given in Fig. 22a. Biomass density probably is more indicative than numerical density of resource exploitation by various size classes.

The size class distribution of a typical high-density sea urchin population at Shemya, from water about 2 to 3 m (7 to 10 ft) in depth and immediately adjacent to the intertidal area, is shown in Fig. 22b. Apparently two peaks are in this distribution, one at 10 to 15 mm in diameter and another at 60 to 65 mm in diameter. The maximum size of sea urchins from this sample is about 87 mm, although individuals over 100 mm in diameter were found while we were specifically searching for large animals. The biomass of sea urchins also is shown in Fig. 22b. A total biomass density of 12,328 g/m² was estimated for the Shemya subtidal sea urchin population in areas of high population density. The biomass of the Amchitka sea urchin population in areas of maximum density was estimated at 1496 g/m². Of total sea urchin biomass density at Shemya, 11,672 g/m² (95%) is contributed by that segment of the population that is larger than the largest sea urchin observed from the Amchitka samples.

At Shemya, at depths of 10 to 15 m (33 to 50 ft), the peak of small animals in the size class

distribution is reduced, and the peak of larger individuals is absent. The biomass density also is reduced to 824 g/m². At these depths 65% of the biomass is contributed by animals larger than the maximum size at Amchitka (Fig. 22c).

At depths of 20 to 25 m (66 to 82 ft), population densities are further reduced, and there are no apparent peaks in the size class distribution. Here the biomass density is reduced to 208 g/m², 39% of which is contributed by animals larger than the maximum size at Amchitka (Fig. 22d).

RESULTS

Intertidal Community

Grazing Studies. At Amchitka sea urchin grazing experiments in *L. longipes* and *H. sessile* zones demonstrated that dense populations of sea urchins could reduce algal cover. Twenty 19-mm-diameter sea urchins grazed 80% of all encaged plants and reduced algal cover by 60 to 70% within 9 months whereas control cages maintained 100% algal cover.

At Shemya both tide pools cleared of sea urchins in September 1971 had a 90% cover of *Ulva lactuca* by June 1972. The larger tide pool contained three *H. sessile* plants and five large sea urchins (about 75 mm in diameter). The smaller tide pool contained no sea urchins. There were no noticeable changes in algal species or in percentage of cover in the two control tide pools from which sea urchins had not been removed.

Limpet grazing experiments conducted in dog dishes on newly denuded rock surfaces in the midlittoral region at Duck Cove and in the midlittoral region and sublittoral fringe at Makarius Bay showed that after 1 year dishes without limpets had 100% algal cover (mostly *U. lactuca* and *H. glandiforme*) whereas dishes with three 30-mm-long limpets had between 2 and 10% cover of the same algal species. Within 1 year after limpets had been removed from the *Halosaccion* zone at Makarius Bay, previously grazed (bare) areas became completely occupied by small red algae (*Rhodomenia* sp. and *I. cornucopiae*). Similar areas where limpets had not been removed remained bare.

Pieces of subtidal and intertidal drift algae placed in small cups containing seawater and either amphipods or isopods were noticeably grazed after 2 days. These algae remained intact when placed in cups containing only filtered seawater.

Field observations showed that drift kelp on the shoreline (composed mostly of subtidal species, such as *A. fistulosa*) provides food and shelter for amphipods (*Orchestia*) and kelp flies (Coelopidae). As kelp decomposes it accumulates around algal holdfasts in calm areas, in small depressions and

tide pools, and around and under rocks. Here many species of abundant amphipods and isopods (often hundreds of individuals per square meter) and sea urchins feed on this algal debris and detritus.

About 5000 Emperor Geese (*Philacte canagica*) spend the winter at Amchitka (Williamson, Emison, and White, 1971) where they feed in the intertidal area during low tide. Field observations and stomach analyses from six adult birds showed that *Ulva* sp. and small red algae (*Porphyra* sp. and *Rhodomenia* sp.), but not kelp, were eaten (Palmisano, 1975). Similar findings were made by Williamson, Emison, and White (1972).

Growth and Feeding Studies. Five intertidal sea urchins from Amchitka doubled in size within 1 year after they were transferred to the marine laboratories at Friday Harbor and kept in a water table containing a constant supply of kelp (Table 5).

The food-preference tests conducted at Amchitka showed that sea urchins from Amchitka and Shemya prefer *L. longipes*, *A. crispa*, and *H. sessile* to *T. clathrus*.

Mussels [*M. edulis* ($\bar{x}$, 18 mm long)] from Puget Sound that had been transferred to Amchitka tripled their size ($\bar{x}$, 58 mm long) in 18 months.

At Friday Harbor, intertidal sea stars from Amchitka, which were fed opened live clams, mussels, and barnacles for 1 year, increased more than one and one-half times in size and more than four times in weight (Table 6). Field observations at Amchitka on 35 feeding sea stars (*L. alaskensis*) showed that small unattached prey, such as crustaceans (amphipods and isopods) and mollusks (clams and snails), comprised over 90% of their diet (by number).

Thais lima from intertidal benches at Amchitka preyed on live barnacles at the University of Washington in Seattle. Field observations on 106 feeding snails (*T. lima*) showed that small littorine snails (*Littorina*) comprised over 93% of their diet (by number). *Thais lima* also preyed on barnacles, where barnacles were abundant in the intertidal region (e.g., Constantine Harbor), and on mussels that had been transferred from Puget Sound to the intertidal region at Makarius Bay.

Siltation Studies. Of 10 dishpans placed in the intertidal area in July 1972, only those enclosing *Hedophyllum* and *Halosaccion* (in high and protected areas) contained silt. The silt averaged 8 cm (3 in.) in depth, and there were no sessile animals or macrophytic plants inside the pans. Pans enclosing *L. longipes*, *C. vancouveriensis*, and *A. crispa* (in low and exposed areas) contained healthy attached algae but no measurable silt.

Fig. 22 – Sea urchin size class and biomass distribution at depths of (a) 18 to 23 m, Amchitka Island, Alaska; (b) 2 to 3 m, Shemya Island, Alaska; (c) 10 to 15 m, Shemya Island, Alaska; and (d) 20 to 25 m, Shemya Island, Alaska.

Silt 1 to 10 cm (0.4 to 4 in.) deep covers large areas of bays and landward edges of wide intertidal benches. No sessile invertebrates or macrophytes were observed in these areas, although the occurrence of crustose coralline algae beneath the silt suggests that the silt cover is absent during part of the year. (See Lebednik and Palmisano, Chap. 17, this volume.)

Silt also accumulates around algal holdfasts and rocks in sheltered intertidal areas and in higher intertidal zones. Little or no silt accumulates at exposed sites or in lower intertidal zones.

Thirty mussels from Puget Sound (10 to 60 mm long) that had been transplanted to the *Halosaccion* zone (high intertidal region) at Makarius Bay in December 1972 were covered with silt and were dead when examined in April 1973. A similar group of mussels transplanted to the *Laminaria* zone (low intertidal region) were alive and free of silt in April and in August 1973.

Settling Studies. No barnacles or mussels set on oyster shells or in the 1-m² denuded rock surfaces at Duck Cove or Makarius Bay. However, a few barnacles (*B. cariosus*) set on the mussels, ropes, and bottles suspended from the dock in Constantine Harbor. Also a few barnacles set at Rifle Range Point in three 0.25-m² areas denuded of *C. vancouveriensis*.

Sea Otter Predation. On several occasions small groups (two to six) of sea otters were observed feeding on intertidal benches (sublittoral fringe) during high tide at Makarius Bay, Rifle Range Point, Duck Cove, and Square Bay. Data collected on three adult sea otters (one with a pup) at Makarius Bay during 30-min sampling periods on five consecutive days in August 1973 showed that

each adult averaged one dive and five sea urchins every 2 min. At this rate one sea otter would eat 150 sea urchins per hour.

During one week in September 1972, sea otters were seen daily at high tide within 1 m (3 ft) of the breakwater at Sweeper Cove, Adak, where the water depth was less than 3 m (10 ft). These animals predominantly fed on sea urchins that were estimated to be 20 to 50 mm in diameter. One adult sea otter was observed for 30 min, during which time it averaged one dive and four sea urchins per minute. At other areas at Adak, sea otters were observed feeding on unidentified food items, although their scats along the rock and cobble shoreline provide evidence that crab, clam, and mussels are consumed.

Approximately 25 sea otters were seen at Chichagof Harbor on Attu. Several of these otters were observed feeding on sea urchins and mussels within 100 m (325 ft) of shore. No other sea otters were seen at Attu. On subsequent visits to Attu in 1975 and 1976, more than 250 and 340 otters, respectively, were counted.

We saw no sea otters during either trip to Shemya. No otters were observed in 1975 or 1976 at Shemya.

Blade Width of *Laminaria longipes*. The blade width of ungrazed *L. longipes* was greater in protected areas than in exposed areas at each of the four islands studied (Table 7).

DISCUSSION

The direct and indirect consequences of sea otter predation on intertidal communities and the effect of predation by sea otters on subtidal

Table 7—Mean Blade Width (mm) of Ungrazed Intertidal *Laminaria longipes* in Areas Subjectively Considered Exposed or Protected (from Wave Shock) in the Western Aleutian Islands, Summer 1972*

Island	Exposed					Protected				
	N	$\bar{x}$	R	SD	CI	N	$\bar{x}$	R	SD	CI
Amchitka	100	34.3†	20 to 45	7.3	±14.4	100	91.1‡	50 to 140	18.8	±37.2
Adak	100	35.4§	22 to 46	6.9	±13.7	100	88.2¶	48 to 140	16.9	±33.5
Shemya	100	24.6**	15 to 38	6.1	±12.1	100	45.8††	28 to 60	13.3	±26.3
Attu	100	23.3§§	15 to 38	5.2	±10.3	100	88.2¶¶	51 to 138	18.0	±35.6

*N, number measured; $\bar{x}$, average individual size in millimeters; R, range of individual sizes in millimeters; SD, standard deviation; CI, 95% confidence interval.

†Rifle Range Point.

‡Makarius Bay.

§Cape Adagdak.

¶Kuluk Bay.

**Urchin Point.

††There were no protected intertidal benches at Shemya; this value came from *L. longipes* plants in a drainage channel near the shoreward portion of the Urchin Point bench.

§§Murder Point.

¶¶Massacre Bay.

communities are discussed, and this information is integrated with theoretical concepts of community organization in an attempt to elucidate the role of sea otters in the nearshore community at Amchitka.

Intertidal Community

Predation can influence the structure of intertidal communities by preventing competitive exclusion or by directly affecting local extinction (Connell, 1961a; Paine, 1966). Wave shock (Ricketts and Calvin, 1968) influences community structure in a similar way in addition to reducing silt accumulation and providing moisture to high intertidal zones. Our study suggests that sea otters can influence both of these factors and therefore are an important factor in determining community structure. We believe that four categories of interactions, based on predation, exist between sea otters and the community. These interactions we define in terms of the primary and secondary consequences of a dense population of sea otters on the rocky intertidal community, i.e., sea otter predation and physical changes in the environment caused by sea otter predation. Rather than considering each organism in the community in relation to sea otters, we will discuss only those obviously affected by sea otter predation. We then will show how various interactions affect the size, density, and distribution of other specific organisms.

Interactions. General consequences of sea otter predation on the rocky intertidal community as we see them are as follows:

Category I: Organisms are directly preyed on by sea otters, e.g., sea urchins.

Category II: Organisms are indirectly affected by biological consequences of sea otter predation, e.g., kelp.

Category III: Organisms are directly affected by physical changes in the environment, which in turn are indirectly caused by sea otter predation, e.g., barnacles.

Category IV: Organisms are indirectly affected by physical changes in the environment, which in turn are indirectly caused by sea otter predation, e.g., predacious sea stars.

These categories are neither mutually exclusive nor independent; they simply are an organizational convenience. Also, we have not experimentally proven that these interactions unequivocally are tied to the sea otter. Other possibilities also will be considered in our discussion. For additional details on the effect of sea otter predation on rocky intertidal communities, see Palmisano (1975).

Category I. Sea otters consume 20 to 23% of their body weight in food daily (Kenyon, 1969). Stomach analyses of (Kenyon, 1969; Lensink, 1962; Burgner and Nakatani, 1972), field observations of (Kenyon, 1969; Estes and Smith, 1973; personal observations), and feeding experiments with captive sea otters, all at Amchitka, show that sea otters are opportunistic predators on benthic intertidal invertebrates (sea urchins, chitons, mussels, limpets, etc.) and bottom-dwelling fishes. This suggests that the dense population of sea otters at Amchitka preys heavily on known food items and is responsible for scarce populations of such intertidal animals as the sea urchin.

High densities of intertidal sea urchins and mussels at Amchitka in the 1930s and at Adak in the 1950s, when sea otters were less abundant on both islands (Kenyon, 1969, and personal communication), and high densities of these intertidal organisms at the islands of Attu and Shemya, where presently there are few or no sea otters, are further evidence (although circumstantial) that sea otters influence populations of these intertidal invertebrates.

The high densities of mussels on vertical intertidal faces at Adak (an island with a dense population of sea otters) suggest that (1) sea otters do not prefer mussels at Adak because other food resources, such as crabs and clams, are abundant; (2) these mussels are inaccessible to sea otters; or (3) some other factor affecting mussels is different between Amchitka and Adak (see discussion near end of category III). If sea otters do prey on these mussels, then continued mussel abundance may be due to good recruitment from areas inaccessible to sea otters. The high density of sea urchins in the breakwater at Adak is probably due to the inability of sea otters to get between the rocks where sea urchins are most abundant. Sea urchins eaten by sea otters in this area probably are those which leave the immediate protection of the breakwater.

We believe that the small size of sea otter food items at Amchitka is due to the sustained influence of resource overexploitation by sea otters. Many predators select large prey because this is energetically the most efficient way of feeding. The growth study conducted at Friday Harbor with intertidal sea urchins from Amchitka proved that these sea urchins are not genetically limited to a small size. Also, their small size is not the result of food limitation in view of the extensive kelp association at Amchitka. This association not only provides a food resource but also a refuge from predation for small sea urchins that live within and around the algal holdfasts. When individual sea urchins leave the protection of the algae or become

too large to be concealed by the holdfasts, they become vulnerable to sea otter predation. Thus protection afforded by the kelp association regulates, to some degree, the size and number of sea urchins susceptible to predation and serves to prevent sea otters from completely eliminating sea urchin populations. The observation of larger sea urchins at Amchitka in the 1930s and the remains of larger sea urchins in Aleut kitchen middens suggest that the present small size of intertidal sea urchins at Amchitka is due to overexploitation by sea otters. Sea urchin sizes at Adak, Shemya, and Attu also support this contention as does the apparent larger size of sea urchins at Massacre Bay (no sea otters) compared with Chichagof Harbor (a small population of sea otters) on Attu.

Other predators could contribute to the low density and small size of individuals in the sea urchin population at Amchitka. Common Eiders (*Somateria mollissima*) and Glaucous-winged Gulls (*Larus glaucescens*) are known to feed on sea urchins and are present at Amchitka (Williamson et al., 1972). These birds, however, also are abundant at Attu and Shemya, and thus apparently they are not capable of significantly reducing individual size or population density of sea urchins.

With this wealth of evidence, we suggest that sea otter predation is primarily responsible for the sparse population of small sea urchins in the intertidal area at Amchitka. For similar reasons, sea otter predation also may be responsible for sparse populations and small sizes of other intertidal invertebrates, i.e., chitons, mussels, and limpets.

Category II. The establishment of sea otters as the major predator of sea urchins at Amchitka and overwhelming evidence in the literature on the grazing effects of sea urchins support the hypothesis that extensive intertidal kelp beds at Amchitka are maintained indirectly by sea otter predation. The experiments at Amchitka (caged sea urchins) and Shemya (sea urchins removed from tide pools) further demonstrate that sea urchins inhibit persistence and development of algal associations.

Algae in the lower intertidal area of Shemya and Attu (islands with few or no sea otters, no offshore kelp beds, but benches and climate similar to Amchitka) were heavily grazed, and algae in comparable areas at Adak (an island with many sea otters, few benches, few offshore kelp beds, but with a climate similar to Amchitka) were ungrazed. These observations suggest that the intertidal algal associations in comparable areas at Amchitka are not maintained solely by extensive benches, offshore kelp beds, or climate. Although all these factors may enhance their development,

algal communities cannot coexist with dense populations of sea urchins. Therefore we believe that the extensive association of intertidal algae at Amchitka exists primarily because of a sparse population of sea urchins.

Experiments conducted at Amchitka showed that grazing by limpets (*C. pelta*) can prevent the development of algal sporelings in small areas. This effect is confirmed by the well-documented results of Shotwell (1950), Jones (1948), and Dayton (1971). Thus it appears that the scarcity of limpets at Amchitka contributes to the development of algal communities.

Although sea otters do feed on limpets, Black Oystercatchers (*Haematopus bachmani*) may depredate this mollusk more severely because limpets are the preferred food of the approximately 300 oystercatchers at Amchitka (Williamson et al., 1972). However, because sea urchins potentially are more destructive to algal communities than are limpets (limpets are slow moving and feed primarily on sporelings and small algae) and because sea otters are more abundant and consume more food, Black Oystercatchers probably are not as important as sea otters in maintaining the association of intertidal algae at Amchitka.

The absence of sea otters and oystercatchers at Attu and Shemya (Sekora, 1973) almost certainly accounts for the dense population of limpets there.

The grazing effect of Emperor Geese on the intertidal kelp beds is negligible because the only plants eaten by geese are small red and green algae.

The wide expanse and dense canopy of *L. longipes* at Amchitka appear to prevent other kelp species from settling and persisting in the sublittoral fringe. *Thalassiophyllum clathrus* is restricted to the subtidal area and tide pools at Amchitka. However, it occurs intertidally at Attu, Shemya, and Adak where *L. longipes* is less abundant than at Amchitka. In the sublittoral fringe at Attu and Shemya, *T. clathrus* settles in the bare patches caused by the grazing of sea urchins. *Thalassiophyllum clathrus* apparently persists here because sea urchins prefer not to graze it (demonstrated by food-preference studies). The short irregular boulder-strewn intertidal bench at Adak probably does not permit *L. longipes* to develop extensive continuous beds and thus to competitively exclude other intertidal kelps, such as *T. clathrus*.

Thalassiophyllum clathrus did not settle in experimentally denuded rock areas at Amchitka, but *C. triplicata*, a subtidal alga at Amchitka, did settle there (Palmisano, 1975). *Cymathere triplicata* was also present in the intertidal area at Adak. Another subtidal kelp, *L. groenlandica*, also

was present in the intertidal area at Shemya and Attu, although not at Adak. Thus it appears that one subtidal kelp occurs intertidally at Attu and Shemya but not at Amchitka because of an indirect effect of sea otter predation, and it occurs intertidally at Adak because of the heterogeneity and narrowness of the bench.

Low-intensity herbivory at Amchitka may enable intertidal algae to outcompete barnacles and mussels for space. Lewis (1964) observed that algae outcompete sessile invertebrates along protected rocky coasts in Great Britain. Dayton (1973) found that algae are competitive dominants over sessile invertebrates in the high intertidal area along the open coast of Washington. Although algae have overgrown some invertebrates at Amchitka, settling experiments showed that neither barnacles nor mussels settle on experimentally denuded horizontal rock surfaces or on oyster shells in protected areas, such as Makarius Bay (areas with few or no barnacles and mussels). Some barnacles did settle on denuded rock in exposed areas, such as Rifle Range Point, on material suspended subtidally from the dock at Constantine Harbor, and on experimentally denuded horizontal rock surfaces at Shemya (areas with moderate to high densities of barnacles). These results suggest that recruitment of sessile invertebrates is closely related to the size and proximity of existing populations. Thus sea otter predation indirectly may cause the dominance of algae and the scarcity of barnacles and mussels on the intertidal bench. On the other hand, those species whose food webs originate from macrophyte productivity, such as the crustaceans (which feed on attached and drift kelp) and the fish they support at Amchitka (Simenstad, 1971; Burgner and Nakatani, 1972; Isakson, Simenstad, and Burgner, 1971), will be absent or scarce where kelp beds have been destroyed or severely reduced by intensive grazing pressure (Simenstad et al., Chap. 19, this volume).

Category III. Many intertidal organisms depend on wave shock to create bare areas needed for larval settling or to prevent accumulation of smothering silt (Ricketts and Calvin, 1968). These organisms are rare in protected environments. Lewis (1964) observed that along the rocky coasts of Great Britain sessile invertebrate associations predominate in areas exposed to direct wave action whereas algal associations occur in more protected areas. Extensive offshore kelp beds can absorb wave energy and thus reduce wave shock to the intertidal area (Moore, 1958; Lewis, 1964; MacGinitie and MacGinitie, 1968).

Weinmann (1968) observed that *L. longipes* have wider blades in protected areas than in ex-

posed areas. The blades of *L. longipes* are wider at the seaward edge of the benches at Amchitka than they are at similar areas at Attu and Shemya (Table 7). This suggests that the intertidal benches at Amchitka are more protected by extensive offshore kelp beds than are similar areas at Attu and Shemya where offshore kelp beds are absent. Blade width is not related to geographical isolation in this situation because *L. longipes* has wide blades in protected areas at Attu (Palmisano, 1975; personal observation) and narrow blades in exposed areas at Amchitka.

At Amchitka barnacles and mussels are most abundant along exposed shorelines. Our experiments show that more silt accumulates in protected areas and higher intertidal zones than in exposed areas and lower intertidal zones. Furthermore, mussels transplanted into known areas of siltation at Amchitka were smothered and eventually died, and barnacles were killed by natural and man-induced increases of siltation at Square Bay and Duck Cove. Therefore the abundant kelp beds at Amchitka, which protect the intertidal area, facilitate siltation and probably, at least in part, are responsible for relatively low densities of barnacles and mussels.

Factors other than offshore kelp beds may be responsible for the depauperate mussel-barnacle association at Amchitka. For example, well-developed intertidal benches also may reduce wave exposure and thus increase siltation. However, there are dense populations of barnacles at Attu and Shemya where benches similar to those at Amchitka exist but where offshore kelp beds are absent.

Mussel and barnacle associations also could be poorly developed at Amchitka because of competition for space, predation, or lack of food. Algal competition may be partially responsible for the scarcity of mussels and barnacles; however, because algae and these invertebrates coexist in the intertidal area at Attu and Shemya, we consider reduced wave shock at Amchitka to be the more important factor.

Mussels and barnacles coexist abundantly with dense populations of predacious snails and sea stars at Attu, Shemya, and Adak. This suggests that predation by mollusks and sea stars, which are less dense and take other prey at Amchitka, is not responsible for the low abundance of barnacles and mussels.

Food is probably not a limiting resource to the growth of mussels or barnacles at Amchitka. Individual large mussels and barnacles occur at Rifle Range Point, Banjo Point, and Constantine Harbor. Also, mussels introduced to Amchitka from Puget Sound tripled their lengths within 18

months. Therefore reduced populations of barnacles and mussels on intertidal benches at Amchitka apparently are more closely related to reduced wave shock than to these other factors.

Barnacle and mussel densities may be high at Adak because of physical factors unrelated to the presence of sea otters. These invertebrates occur there on vertical surfaces not subject to accumulation of silt. Also, although the convoluted coastline is protected by its very physical nature at Adak, there are few offshore kelp beds (because of unsuitable substrates) to absorb wave energy and no wide benches to reduce wave shock.

Thus, although purely physical factors, such as bays, islets, and reefs, do affect intertidal communities by reducing wave shock, the evidence suggests that sea otter predation at Amchitka is the major cause of such physical changes and thus in turn has prevented the development of extensive barnacle and mussel beds in the intertidal community.

Category IV. Organisms limited by barnacle or mussel beds as critical resources may be rare or absent and reduced in size where these beds are absent. For example, at Amchitka *T. lima* prey almost exclusively on small littorine snails and *L. alaskensis* prey on small mollusks and crustaceans. *T. lima* and *L. alaskensis* may be small and scarce on the benches at Amchitka because their individual food resources are small and spatially dispersed (i.e., not clumped); they probably would be larger and more abundant if food resources were large, sessile, densely clumped organisms, such as barnacles and mussels. This hypothesis is supported by the coexistence, at Attu, Shemya, and Adak Islands, of large *T. lima* and large *L. alaskensis* with dense populations of barnacles and mussels. Evidence that these predators at Amchitka are not genetically limited to a small size is provided by the fourfold increase in weight at Friday Harbor of *L. alaskensis* removed from Amchitka and by the occurrence of large *T. lima* in Constantine Harbor and at Banjo Point, areas of relatively high densities of barnacles and mussels.

The abundance and size of *T. lima* may also affect hermit crab (*Pagurus*) populations. Hermit crabs require a shell resource; over 90% of the hermit crabs at Attu, Shemya, and Adak occupied *T. lima* shells. The scarcity of these shells on the intertidal bench at Amchitka apparently is one reason why hermit crabs also are not abundant there. Carl F. Nyblade (personal communication) stated that abundant littorine snails at Amchitka should provide a suitable shell resource for *P. hirsutiunculus* even though these shells are considerably smaller than *T. lima* shells. Palmisano

(1975) speculates that this resource is destroyed by marine birds that prey on littorines.

Alternately the sparse hermit crab population at Amchitka could be caused by an inadequate food resource, by unsuitable habitat, or by fish predation. The specific food requirements of hermit crabs are poorly known, but adequate food should be available at Amchitka for these detritus feeders. Shemya has more tide pools than Amchitka or Attu, but Attu and Shemya have comparable hermit crab densities. Thus tide pools apparently are not essential for hermit crab survival. Hermit crabs are also abundant at Adak where there are a few tide pools and an abundant supply of *T. lima* shells but unfortunately an unknown effect of predation by nearshore fishes. Therefore our observations suggest that the sparse population of hermit crabs at Amchitka is caused either by a lack of suitable shells or by predation of fish from the kelp community.

Finally, the small size and low densities of predacious snails and sea stars and the low density of hermit crabs at Amchitka may be physically maintained by low wave shock, which in turn is ultimately caused by sea otter predation on epibenthic invertebrates.

Subtidal Community

Species Diversity in the Nearshore Community. Increased species diversity in both terrestrial and marine environments is a phenomenon generally observed as one progresses from the Arctic to the tropics (Hedgpeth, 1957; Fischer, 1960; Sanders, 1968; MacArthur, 1972). Exceptions to this general pattern are the kelps (Phaeophyta) and red algae (Rhodophyta) and several terrestrial groups (Fischer, 1960). A review of several theories on causal factors responsible for increased species diversity in the tropics in light of his own data on species diversity of the deep-sea benthos led Sanders (1968) to the stability-time hypothesis. Briefly, this hypothesis proposes that physically severe (unstable) environments tend toward an abiotic condition, allowing the existence of only a limited number of species. Stable environments, on the other hand, given sufficient time develop diverse biological communities. Recently this hypothesis was challenged by Dayton and Hessler (1972) who argued that high-species diversity is not necessarily solely the result of competitive niche differentiation but is also caused by predictable disturbances, which reduce the importance of competitive exclusion and thus allow the coexistence of many species who share the same resources.

The importance of disturbance in structuring certain communities is clear. In theory, a pre-

dictable disturbance releases a critical resource, such as light, space, and nutrients, from monopolization by species with superior competitive ability. Thus a diverse community is maintained so long as resources are available to fugitive species. In the absence of disturbance, the tendency of some species toward local extinction is predicted.

The importance of predation as a source of local predictable disturbance was proposed by Paine (1966) and further supported by observations by Paine and Vadas (1969), Connell (1970), Dayton (1971), and others. Paine (1966) found that species diversity is related directly to the efficiency with which predators prevent monopolization of major environmental requisites by competitively superior species in intertidal communities. In his studies predator removal led to local extinction of certain invertebrates and algae. The ecosystem thus became trophically simpler with decreased diversity and decreased primary productivity.

Earlier studies of sea otter food habits in the western Aleutian Islands (Lensink, 1962; Kenyon, 1969; Burgner and Nakatani, 1972) suggest that sea otter predation is an important community interaction. During recent years at Amchitka Island, invertebrates and fish have contributed approximately equally to the sea otter's diet. Studies by Kenyon showed at least 42 species of food items from sea otter stomachs. In the analyses by Burgner and Nakatani, although food items were not reported as individual species, 15 different food items were reported from stomach analyses. Stomachs used in Kenyon's studies were collected from Amchitka in 1962 and 1963, a time when the sea otter population had been at equilibrium density for at least a decade. Stomachs used in the study by Burgner and Nakatani were collected at Amchitka in 1970 and thus also are from a sea otter population at equilibrium density. Lensink (1962) reported analyses of sea otter feces collected at the Komandorskie and Aleutian Islands in the 1930s and 1940s. Only six food items were reported from these observations with sea urchins and mussels composing nearly the entire volume. Lensink's studies indicated that the sea urchin was the dominant sea otter food item at Amchitka and other Aleutian Islands during the late 1930s and 1940s. The later studies of Kenyon (1969) and Burgner and Nakatani (1972) showed an increase in diversity of food items consumed by the sea otter. Of particular interest is the increased amount of fish in the sea otter's diet during recent years. Although techniques used by these various investigators are not strictly comparable, the general pattern of change in sea otter food habits through time is certainly significant. During early stages of

population recovery, the sea urchin was apparently the primary food item; later, as the sea urchin population was reduced by sea otter predation, invertebrate community structure and/or sea otter foraging strategies changed. This was reflected as an increased diversity in sea otter forage items, paralleling temporally the development and establishment of high-density sea otter populations.

Similar observations and conclusions have been made on the sea otter in California. A profound decrease in sport and commercial abalone fisheries has been reported following the influx of sea otters into areas of previously unoccupied habitat (Wild and Ames, 1974; Miller, Geibel, and Houk, 1974). A survey conducted in 1967 by the California Department of Fish and Game revealed that, throughout the sea otter's range, preferred forage items were reduced in number and restricted to protected habitat as compared with habitat outside the range (Ebert, 1968). Also, an increased diversity in sea otter forage items has been reported in areas long inhabited by sea otters. This is apparently the result of reduced availability of preferred sea otter forage items (Wild and Ames, 1974).

Thus the role of the sea otter in structuring nearshore marine communities fits nicely into the predation model of Paine (1966). Our observations from Attu and Shemya suggest that the absence of sea otters allows sea urchins to monopolize subtidal communities, and "dominance diversity" (Sanders, 1968, p. 260) is very low. At Amchitka a high-density sea otter population prevents monopolization of subtidal resources by sea urchins so that dominance diversity is higher than at Attu and Shemya. Thus, in addition to general observations on community structure, studies of sea otter food habits in the Aleutian Islands and in California further support the role of the sea otter in maintaining a diverse community.

Sea otter food habits also certainly are affected by food availability (or energy abundance). Schoener (1971) and MacArthur (1972) presented theoretical arguments that relate feeding strategies to food availability. Schoener's model considers species from an energy-time standpoint, and from it he concludes that there is an optimum number of species in the diet of a predator at any given general prey density which will yield a maximum amount of energy per amount of time expended in procuring food. This model predicts that, as prey density increases, there is a decrease in the number of species that should be included in a predator's diet to maximize energy yield. MacArthur's model is based on time economy and prey selection but reaches a conclusion similar to the Schoener model. As prey density decreases, species diversity

in prey selection increases. Numerous examples that support this conclusion are found in the literature, and it is reasonable to expect that the array of food items used by sea otters will increase as exploitation due to predation decreases the general food abundance.

The control of sea urchins by sea otter predation releases algal associations from overgrazing and thus increases vegetational biomass and primary productivity. Species associated with subtidal primary productivity are influenced indirectly. Sea otters, therefore, may influence species diversity through two basic mechanisms: (1) Species diversity may be increased by reduced competition with sea urchins or other epibenthic invertebrates for environmental requisites and (2) species diversity may be increased indirectly by increased primary productivity that results when grazing pressure by an uncontrolled sea urchin population is released. Thus sea otters increase diversity and primary productivity and perhaps lend stability (Sutherland, 1974; but see May, 1973)* to near-shore communities.

This discussion logically leads to the influence of overexploitation of food resources by the sea otter. Paine and Vadas (1969) reported that algal associations of low species diversity are maintained not only by sea urchin overgrazing but also by undergrazing in areas devoid of sea urchins. In the absence of urchin grazing pressure, dominant algal species tend to exclude competitively other species and to monopolize the vegetational association. Intermittent sea urchin grazing provides a release of heterogeneous space, allowing the colonization of fugitive algal species. This process increases the number of coexisting algal species. Maximum algal species richness, therefore, should be approached when the sea urchin population is balanced between overexploitation and underexploitation of the plant association.

Sea otters undoubtedly exploit the Amchitka sea urchin population heavily. Can this, in fact, be considered overexploitation, and, as a consequence, is the macroalgal association monopolized by dominant species? Our data from the shallow subtidal area at Amchitka suggest that in many areas four species of *Laminaria* dominate the epibenthic canopy; sea urchins, other than small individuals associated with haptera or protective crevices, are rare. This observation in itself is open to the interpretation of monopolization by a single

species or several species within the genus. Another factor of probable importance as a source of disturbance is the frequent and violent winter storms of the Aleutian Islands. Walker and Richardson (1955) state that *Laminaria* is torn from the sea bed during heavy winter storms around Scotland. Large deposits of vegetation on the beaches of Amchitka following violent storms indicate a similar situation there. Therefore storms also may provide a mechanism for the release of space and thus the colonization of fugitive species.

Sea Otter and Pattern in the Nearshore Algal Association. Hutchinson (1953) stated that community patterns are determined by stochastic processes, physical forces, and biological forces. We will discuss the basic sublittoral community patterns at Amchitka Island according to Hutchinson's scheme. Our tentative opinion as to the causal factors of these patterns is based primarily on the discussion and conclusions from studies of ecologically similar areas. Final acceptance or rejection of these conclusions as they apply specifically to western Aleutian communities depends on direct experimental evidence, which is presently lacking.

Generally, community patterns are similar in coastal north temperate and boreal waters of the Atlantic and Pacific Oceans (Kitching, 1941; Walker, 1947; Jorde and Klavestad, 1963; Kain, 1966; Vadas, 1968; Himmelman and Steel, 1971; Mann, 1972a; and others). Sublittoral macrophyte associations are well developed on rocky substrates throughout this geographic range. Various species of *Laminaria* are dominant in the shallow kelp zone, and *Agarum* frequently is found in slightly deeper water. Sea urchins are the dominant benthic invertebrate in many of these communities.

Connell (1961a) proposed a general theory to explain the rather sharply defined pattern of zonation in rocky intertidal communities; i.e., physical factors limit the upper distribution and biological factors limit the lower distribution of species. Sublittoral communities are apparently less strictly defined spatially (Kitching, 1941) with their upper and lower limits of species distributions not universally defined by physical and biological forces, respectively.

Vadas (1968) stated that the distribution of subtidal algae may be limited by temperature, salinity, light, suitable substrate, exposure, and biological interaction; however, he stressed the importance of predation and competition.

Stochastic Processes. Some variation of sublittoral community structure is undoubtedly the result of stochastic processes. Because large sample sizes are required for adequate analysis of this factor and because we believe the overwhelming

*The dogma that complexity begets stability in ecological systems has recently been challenged (May, 1973). A detailed discussion of diversity-stability arguments is inappropriate here. We only wish to point out that the nature of diversity-stability relationships is conjectural.

evidence points to physical and biological causality in the communities observed, stochastic factors will not be considered here.

Physical Forces. Of the physical factors discussed by Vadas (1968), all but light probably can be discounted as a causal factor dictating patterns in the association of subtidal macrophytes at Amchitka. Temperature and salinity are generally constant throughout the depth range studied. All study areas were located on solid-rock substrates with nearly constant slopes. The four study areas at Amchitka varied in exposure from well protected to heavily exposed, but no consistent pattern can be attributed to this factor. Physical factors also are generally similar in the Rat and Near Islands.

The abundance of vegetation decreases with increased depth in the subtidal area at Amchitka. This observation is consistent with the pattern of other subtidal plant associations over a wide geographical range (Walker and Richardson, 1955; Jorde and Klavestad, 1963; Kain, 1966; Walker, 1947; Aleem, 1956; McLean, 1962; Mann, 1972a). (Light attenuation as depth increases is certainly one factor responsible for this pattern.) Also, red light and blue light are selectively absorbed by clear ocean water, and green light penetrates most deeply. Because the action spectrum of green and brown algae is restricted primarily to blue light and red light, these plants are limited in depth by the shallow penetration of light that they require for photosynthesis. Red algae, which uses the reduced light beneath the lower canopy (Dawson, Neushul, and Wildman, 1960) and the deep penetrating green light (Blinks, 1955) in photosynthesis, are thus abundant throughout the depth range of the brown and green algae and beyond it.

Biological Forces. High-density sea urchin populations have been reported to be responsible for the scarcity of noncoralline algae in many areas (Himmelman and Steele, 1971; Kitching and Ebling, 1961; Vadas, 1968; and others). We believe that the high-density sea urchin population at the Near Islands is responsible for the virtual absence of fleshy macrophytes in subtidal areas.

Conversely, sea urchin densities at Amchitka are extremely variable. However, sea urchins are rare in shallow areas. At Amchitka sea urchin densities increase with increasing depth (Fig. 19), and grazing pressure, therefore, may be partially responsible for the pattern in vegetation abundance.

Vadas (1968) found that *Laminaria* was the climax genus in the absence of grazing in the San Juan Islands. In the presence of moderate grazing pressure on *Laminaria*, *Agarum* entered the com-

munity as a result of reduced competition with *Laminaria* for light. He found that, although *Laminaria* was dominant over *Agarum* in the undisturbed community, *Agarum* was resistant to urchin grazing and became established in the presence of moderate grazing disturbance.

At Amchitka *Laminaria* is apparently able to completely exclude *Agarum* in shallow water [mean water level to about 7 m (23 ft) in depth]. At the lower edge of this shallow zone, *Laminaria* is apparently limited by decreased light and perhaps also by increased sea urchin grazing, thus allowing *Agarum* to enter the vegetation association.

Mechanisms of Sea Urchin Population Regulation. There are two classically understood methods of population regulation. First, populations may be limited by resources, in which instance intraspecific or interspecific competition limits population growth. Requisite resources include nutrients, space, and light. Disturbances also may limit populations. Disturbances operate as biological (predation) forces and/or physical forces, such as catastrophic events and physiological barriers.

The upper distribution of sea urchins at Attu and Shemya appears to be limited by disturbance. At low tide Glaucous-winged Gulls (*L. glaucescens*) are commonly observed feeding on large sea urchins. The upper distribution of sea urchins also is physiologically limited because urchins require almost constant exposure to fresh seawater. At the edge of this area, we frequently observed sea urchins moving up and down with the incoming and outgoing tides. Physiological limitations probably primarily determine the upper limit of sea urchins at the Near Islands.

The lower limit of sea urchins at Attu and Shemya is below depths that we were able to dive with scuba. However, the decrease in population density that we observed at greater depths indicates that the population is more severely limited there than in shallow water. Because there are no apparent sources of disturbance to the sea urchin population at these depths, we believe that the deeper distribution of the population is primarily resource limited, probably by nutrients, such as macrophytes. Drift algae are also probably important to the distribution of sea urchins at Attu and Shemya. After storms, moderate accumulations of algae are observed on the beaches at Attu and Shemya. The majority of this material that is not washed ashore settles in the shallow subtidal area and thus serves as a source of nutrition for herbivores. In support of this idea, Fig. 23 shows sea urchins congregated about a strand of *A.*

Fig. 23—Sea urchins massing about a strand of *Alaria fistulosa* that has drifted into a large tide pool in lower intertidal area at Shemya Island, Alaska (Sept. 2, 1971).

fistulosa that had drifted into a large tide pool of the lower intertidal area at Shemya. Also, while diving on Attu we encountered several groups of sea urchins massed together in the form of a sphere. We separated one of these spheres and found a small piece of *Thalassiophyllum* blade near its center.

Displacement of nutrients by wave action from the large standing crop of intertidal macrophytes may also be important to sea urchins in the shallow subtidal area at Attu and Shemya. In fact, apparently there is almost no source of nutrient production sympatric with subtidal sea urchin populations. The expected distribution of nutrient input (drifting algae from other areas and nutrients washed from the intertidal area) corresponds closely with observed distribution of sea urchins.

In direct contrast to the distribution of sea urchins at Shemya and Attu, sea urchins at Amchitka are most severely limited in the im-

mediate subtidal area, and population densities increase in deeper water (Fig. 19). We believe that sea otter predation is primarily responsible for this distribution. Certainly the abundant standing crop of algae at Amchitka would preclude sea urchins from nutrient limitation! Competition for space with the well-established algal association also seems unlikely, although the physical and biological configuration of the bottom may influence larval settling (Crisp and Barnes, 1954). Perhaps predation from diving birds, fish, or other invertebrates is of some significance, but the potential impact of sea otter predation is logically the most important limiting factor. As at Attu and Shemya, depth limitations in the use of scuba prevented us from observing the lower distributional limits of sea urchins at Amchitka.

At Attu and Shemya we observed numerous sea urchins with abraded areas on the outer surface of their tests. This was never observed at Amchitka. Himmelman and Steele (1971) noted test abrasions in *S. drobachiensis* which they attributed to cannibalism when insufficient food was available. We have no direct evidence that the bare areas on sea urchin tests at Attu and Shemya were caused by cannibalism, but it seems logical that population crowding is somehow involved.

r- or K-Selection? The concept of r- and K-selection was conceived originally by MacArthur and Wilson (1967) to explain reproductive strategies of species that are closely associated ecologically. In an uncrowded environment, selection preference is extended toward r-strategists or toward species with the highest intrinsic rate of natural increase. The strategy is to convert a maximum amount of food into new members of the population. In a crowded environment, i.e., one in which populations exist near equilibrium density, K-strategists are favored. Efficiency of food use is important in maintaining large populations, and wasteful exploitation of food resources, such as for the production of large numbers of offspring, is selectively unfavorable (Crow and Kimura, 1970). Pianka (1970) summarized some of the correlates of r- and K-selection, a few of which are given in Table 8.

From our prior discussion and from the information given in Table 8, sea urchins at Amchitka appear as r-strategists whereas those at Attu and Shemya appear as K-strategists. This is unlikely because we are dealing with a single species. Thus we expect these populations to be similar genetically and either r- or K-strategists but certainly not both.

We propose that, whereas sea urchins at Attu and Shemya fulfill many requirements of K-

Table 8—Some Correlates of r- and K-Selection*

Item	r-selection	K-selection
Mortality	Often catastrophic, density independent.	Density dependent.
Survivorship	Often type III (Deevey, 1947).	Usually types I and II (Deevey, 1947).
Population size	Variable in time, non-equilibrium; usually well below carrying capacity of environment; unsaturated communities or portions thereof; ecological vacuums.	Fairly consistent in time, equilibrium; at or near carrying capacity of the environment; saturated communities.
Intraspecific and inter-specific competition	Variable, often lax.	Usually keen.

*From E. R. Pianka, On r- and K-Selection, *American Naturalist*, 104: 593 (1970).

strategists, the species has evolved through r-selection. Thus the tendency toward maximum energy exploitation by an uncontrolled r-strategist is incompatible with maintenance of the energy resource (e.g., macrophytes are destroyed).

Sea Otter and Productivity of the Nearshore Community. Benthic macrophytes are of considerable importance to nearshore productivity in temperate waters. Blinks (1955) stated that, although littoral marine algae occupy only a narrow coastal zone as compared with the entire ocean, their productivity may be several orders of magnitude greater per comparable unit than the open sea except in areas of upwelling. Mann (1972b; 1973) found that forests of *Laminaria* and *Agarum*, which characterize the subtidal area of temperate oceans, contribute considerably to the total productivity of coastal waters in the North Atlantic Ocean. He attributed this to the attachment of plants on the rocky substratum and thus to an unusually good supply of nutrients circulated by tides and currents. Significantly the range of feeding habitat of sea otters coincides with, and extends beyond, the area of epibenthic algae. As such the sea otter may indirectly maintain the kelp beds (see earlier discussion).

Some animal species present at Amchitka but scarce or missing at Attu and Shemya may depend on the highly productive macrophytic algae as a nutritional base. Those animal species whose food webs originate from macrophyte productivity certainly could be adversely affected by its removal (Paine, 1966).

The rock greenling (*Hexagrammos lagocephalus*), abundant and commonly encountered while diving at Amchitka, is infrequently seen at

Attu and Shemya. This species feeds largely on crustacean invertebrates, which, in turn, are associated with kelp beds (see earlier discussion). Higher trophic forms at Amchitka, which are dependent on fish for some part of their food, probably either use different foraging strategies or maintain smaller populations at Attu and Shemya. Sea otters consume greater amounts of fish at Amchitka than in areas of low sea otter population density (Lensink, 1962). Harbor seals (*Phoca vitulina*) are less common at Attu and Shemya than at Amchitka where groups of over 100 commonly haul out at numerous areas along the coast (Kenyon and King, 1965). Harbor seals feed predominantly on nearshore fishes and cephalopods at Amchitka (Wilke, 1957; Kenyon, 1965).

The Bald Eagle (*Haliaeetus leucocephalus*), although abundant in the Rat Islands, is absent in the Near Islands (Sekora, 1973; personal observations). Bald Eagles in the Aleutians are largely dependent on marine productivity. Fish, marine mammals, and marine birds have been found to constitute the majority of their diet on Amchitka (White, Emison, and Williamson, 1971). Also, drift algal stipes are major constituents of Bald Eagle nests at Amchitka Island (personal observation). The absence of eagles in the Near Islands may therefore be related indirectly to reduced macrophyte productivity.

The Common Eider (*Somateria mollissima*) is by far the most common duck in saltwater areas of Attu Island (Near Islands) (Byrd, 1973). This species probably owes its high density to the sea urchins (Byrd, 1973). Although the Common Eider is present at Amchitka, it is not nearly so abundant there as at Attu, probably reflecting the decreased availability of sea urchins at Amchitka Island.

Sea otters also may contribute to the growth of kelp beds (and associated species of animals) along much of the west coast of North America. McLean (1962) reported that sea otters in California completely remove large sea urchins (*S. franciscanus*) from areas by predation, permitting luxuriant development of the *Nereocystis-Pterygophora* association. North (1965) attributed recent kelp bed (*Macrocystis*) reduction to sea urchin grazing and further speculated that an increase in *Macrocystis* density in the Monterey area resulted from sea urchin removal by sea otters. Miller and Geibel (1973), however, point out that recent changes in distribution and abundance of *Macrocystis* and *Nereocystis* in many areas are related to factors other than sea otter predation. Thus, although sea otters clearly reduce benthic invertebrate populations in these areas of the California coast, other interactions are not well understood.

The Aleut has inhabited the eastern Aleutian Islands for at least 8400 years (Laughlin, 1972) and Amchitka for at least 2500 years (Desautels et al., 1970; McCartney, Chap. 5, this volume). Laughlin (1972) believed that the Aleut influenced the sea otter by direct exploitation through hunting and competition for food resources by gathering sea urchins. We doubt that the Aleut was able to compete with sea otters for food, although Aleuts collected sea urchins from the intertidal and very shallow subtidal zones. However, Aleuts certainly were capable of reducing sea otters by hunting, as is evident from the fact that sea otters were driven nearly to extinction by Aleuts after they were enslaved by Russian fur traders. Furthermore, evidence from middens suggest that Aleuts depleted sea otter populations long before the arrival of white men. However, from the standpoint of evolutionary time, the Aleut is recent. Thus his importance as a natural predator in the nearshore community is not yet clear.

Some of the preceding discussion is speculative. However, the sea otter quite obviously is an important species in determining structures and dynamic relationships with nearshore communities, thus fitting the concept of Paine (1969) of a keystone species. Until the recent resurgence of sea otters on the Pacific coast, biologists were unaware of the influence of sea otters on intertidal and subtidal communities within the original range. Our studies indicate that the sea otter was a significant factor in the evolution of the nearshore ecosystem of the North Pacific Ocean.

CONCLUSIONS

That sea otters are capable of reducing both the size and number of sea urchins is indicated by their voracious appetite, analyses of their stomach contents, and feeding observations of wild and captive animals. The overwhelming evidence in the literature and the results of grazing experiments conducted at Amchitka and Shemya clearly demonstrate that marine vegetation flourishes in the absence, but is destroyed in the presence, of dense populations of sea urchins. From further observations of similar areas in the western Aleutians with and without sea otters (both in time and space), we conclude that in the nearshore community at Amchitka sea otters are directly responsible for the reduction of the size and number of sea urchins within their feeding range and indirectly responsible for the resultant development of extensive algal beds and associated communities. Because these kelp beds can alter physical conditions in the intertidal community by

reducing wave shock and increasing siltation rates, we further conclude that sea otters are indirectly responsible for the sparse populations of barnacles and mussels and for the small size and low number of predacious snails and sea stars and the small number of hermit crabs.

It is possible that physical factors, such as intertidal benches, coastline features, and climate, or other biological factors, such as other predators and competition resource shortages, are partly or fully responsible for the structure of the nearshore community at Amchitka. However, comparisons of western Aleutian nearshore communities, similar in most aspects except for densities of sea otter populations, and the results of field and laboratory experiments strongly indicate that the sea otter is the keystone species at Amchitka that is primarily responsible for the observed structure of the nearshore community.

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APPENDIX: PARAMETER INTERVAL ESTIMATION AND TESTS OF SIGNIFICANCE IN THE LINEAR MODEL $y_i = \mu + \beta(x_i) + e_i$

Variance ($\hat{\mu}$) = 1.454 ± 2

Variance ($\hat{\beta}$) = 1.174

95% confidence interval (μ) = -8.114 to -7.636

95% confidence interval (β) = 2.924 to 3.059
t-test of hypothesis ($\mu = 0$) $t = 65.307^*$ with 111 degrees of freedom

t-test of hypothesis ($\beta = 0$) $t = 87.310^*$ with 111 degrees of freedom

Analysis of variance for linear regression

Source of variation	Degrees of freedom	Sum of squares	Mean square	F
Due to regression	1	289.226	289.226	7623.1*
Residual	111	4.211	0.0379	
Total	112	293.437		

*Significant at 0.01 level.

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Sea Otter Metabolism and Heat Economy

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In ten 13- to 33-kg sea otters captured and maintained at Amchitka Island, a basal metabolic level of $0.72 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$ was found in 17 values measured over thermoneutral zones of -20 to 21°C in air and 20 to 33°C in water. Average values of 1.0 and $1.2 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$ and maximum values of 1.9 and $2.6 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$ in air and water, respectively, confirm the high food demand of one-fifth to one-fourth their body weight in fish daily. Minimum thermal conductance in air, $<0.012 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1}$

$\text{hr}^{-1}^\circ \text{C}^{-1}$, was greater for these mammals than for terrestrial arctic mammals, but it only increased twofold on immersion in water. Water infiltration into the fur above 25°C allowed survival at even 33°C . Body temperature was regulated under neutral conditions at $38.1 \pm 0.34^\circ \text{C}$ (mean $\pm$ standard deviation), under cold conditions at $36.7 \pm 0.45^\circ \text{C}$, and under warm conditions at $38.5 \pm 0.31^\circ \text{C}$ with 44.1°C as a single lethal value.

The sea otter (*Enhydra lutris*) is a species of extraordinary interest both historically and biologically. Its valuable fur and its vulnerability led to its extermination in many areas, and only in recent years through protection and transplanting procedures has it become established in many locations so that it is no longer in danger of extinction (Kenyon, 1969; Estes, Chap. 21, this volume). The sea otter is the largest of the Mustelidae, being rivaled only by the giant Amazonian otter (*Pteronura brasiliensis*), itself threatened with extinction. Among the Mustelidae it is the only truly marine form and as such the most adapted for aquatic life. Although its northern habitat may appear severe and stressful, it is, in fact, of a very constant nature, rivaling or even exceeding the tropical rain forest in its uniformity.

Because of isolated distribution and problems of capture and maintenance, almost nothing is known of its physiological attributes beyond a few body temperatures (Irving and Krog, 1954; Stullken and Kirkpatrick, 1955). Accordingly, such observations are of much interest as comparative physiology and in terms of practical problems in

handling and maintaining these animals that have appeared sensitive to thermal adjustment, restraint, disturbance, food requirements, and fouling.

These observations emphasized such bioenergetic parameters as basal metabolism (M_b), average metabolic rate (M_{av}) in air and in water, the maximum metabolic rate (M_{max}), the lower critical temperature that calls for thermoregulatory heat production, the upper critical temperatures in air and water above which body temperature (T_b) increases and presents a hazard in maintenance, and the T_b levels that are associated with transition points or with ambient temperature levels (T_a). A more detailed report on these observations has been published (Morrison, Rosenmann, and Estes, 1974).

METHODS

The large size, vigor, behavior pattern, and isolated habitat, which make this species of interest, posed real technical difficulties in handling and instrumentation. The animals, ranging in weight from 13 to 33 kg, were taken in nets near Constantine Harbor or East Cape. They were held outdoors and supplied with running seawater in large (20 by 24 ft) wooden tanks that had been constructed by the Alaska Department of Fish and Game for their transplantation program. Frozen

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fish filets and squid were supplied twice daily in an amount equal to roughly 20% of the body weight per day. Although some sea otters are sensitive and die outright of shock following netting or handling, once established in tanks most are maintained in excellent condition.

Most experiments were begun in the morning some 15 hr after the last feeding. This is well past the 3-hr period reported by Kenyon (1969) for the passage of food through the gut. No metabolic differences were observed in five runs begun 6 hr and in two runs begun 3 hr after feeding. Animals were lost in two such early experiments (one each in water and air), apparently from shock since there was no other demonstrable cause. No unusual excitement or depression was observed, but the animals suddenly stopped breathing. Thereafter no problems were encountered in some two dozen experiments under conditions ranging from water at 33°C to the equivalent of air below -70°C for durations up to 8 hr. Forceful handling was necessary, especially in measuring body temperature, but our overall view of the sea otter as an experimental animal was very favorable.

Metabolic measurements used a closed-circuit automatic manometric system that recorded the time required to consume successive aliquots of oxygen (Morrison, 1951). In the basic arrangement

the subject occupied a wire cage (35 by 35 by 100 cm) within a larger metal box with a Lucite cover. Lateral screened trays filled with barium hydroxide lime absorbed CO₂. A refrigerated bath (to -30°C) maintained the T_a down to -20°C, a modest stress for a large well-furred animal. Greater thermal stress was provided by a 4:1 helium-oxygen atmosphere which increased heat transfer by some twofold, giving a thermal equivalent of -70°C in air (Rosenmann and Morrison, 1974).

Alternately, the subjects were enclosed directly in a large water bath (60 by 60 by 120 cm) with the air space above connected to the manometer control (Fig. 1). One external circulation through a barium hydroxide lime canister removed CO₂ from the air phase and a second through particle and charcoal filters removed sediment and organics from the water phase. The temperature of the latter circulation was monitored, and heat was added or removed to maintain the desired T_a. Although the volume of the system was greatly increased, the incompressibility of the aqueous phase allowed the animals to dive and swim freely without compromising the manometric control. Body temperature (T_b) was measured before and after metabolism runs with a thermistor probe with 8- to 12-in. rectal insertions.

Fig. 1—Diagram of experimental arrangement for metabolic measurements in water.

RESULTS AND DISCUSSION

Basal Metabolism and the Thermoneutral Zone

Metabolism was measured in air in 12 experiments at T_a ranging from 23 to -20°C . Individual experiments reflected bouts of activity with intervening quiet periods (Fig. 2) which provided acceptable values for M_b in 10 cases (averaging the three lowest points in each). These values showed no trend with T_a over the range of -19 to 21°C , which is thus within the thermoneutral zone (Fig. 3). The average of these values, $0.72 \pm 0.06 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$, lay far above the standard metabolism (M_{st}) of $0.27 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$ for an 18-kg mammal.*

In 14 experiments the metabolism was measured in water at temperatures ranging from 5 to 33°C . Although the animals responded well, the greater freedom for movement resulted in fewer resting or inactive periods. Overall the minimum three values in 13 runs in water averaged $0.85 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$, about 20% higher than in air. However, at higher temperatures the animals appeared sedated, and good periods of sleep were observed in two runs. These values, taken with the four lowest values in air, give a mean of $0.67 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$, which may better represent a limiting basal value.

The M_b of 0.67 to $0.72 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$, with consistent values measured over a wide range of T_a and in two media, appears to be a very reliable value, and yet it is 2.5-fold higher than the M_{st} for a mammal of this size (i.e., at 2.5 met). To assess the implications of this difference, we must compare other species. The Mustelidae as a family with their vigor and carnivorous mode do show a range of M_b . However, in the Wisconsin least weasel (*Mustela rixosa*), for which more data are on hand, the minimum values were less than 1.2 met, and, in the ferret (*Mustela putorius*) and tayra (*Eira barbara*), values below M_{st} were observed (Morrison and Ryser, 1976). Recently Iverson (1972) reported values on a series of European mustelids ranging in size from the weasel (*Mustela nivalis*) (at near 100 g) to the wolverine (*Gulo gulo*) (at 15 kg). Values in the latter species, which is comparable to our sea otters in weight, were 1.3 to 1.4 met and that in the badger (*Meles meles*),

whose weight was 10 kg, was only 0.9 met. Of particular interest were values on river otters (*Lutra lutra*) weighing 7 to 10 kg which ranged rather widely from 1.4 to 2.0 met. Accordingly, the Mustelidae as a group do not show an elevated M_b .

When other marine mammals are compared, we do find a correspondence. Irving (1969) summarized earlier data showing high M_b values of 1.7 to 2.1 met in young seals and 2.3 to 2.9 met in porpoises, and these values have been confirmed in recent studies on both groups (Hampton et al., 1971; Miller et al., 1973; Iverson and Krog, 1973). The last investigators also report a single point (figure only) for a 40-kg sea otter at 2.8 met. Øritsland (1973) recently reported an M_b below M_{st} in a harp seal, but 40% of the 130-kg weight was thought to represent blubber. Thus it is of much interest to find this effect in a marine that is representative of a third mammalian order. This phenomenon has evaded explanation for some time since it does not relate in any obvious way to the primary adaptation to diving and in fact seems a deterrent in a specialization that is directed toward oxygen conservation during dives. Neither does it seem reasonable that the maintenance cost of the biological system should be higher in such marine forms; so one must look elsewhere for explanation.

Another notable example of elevated metabolism is seen in that very small mammal, the long-tailed shrew (*Sorex cinereus*), for which we earlier proposed an explanation that may also apply to the sea otter (Morrison and Pearson, 1946; Morrison et al., 1959). Although the two species differ in mass by some 5000-fold and in metabolic rate and feeding cycle length by some 10-fold, they may both be thought of as "carnivorous grazers" who take food from a restricted local range as needed. Since the diet is largely protein, it must exceed the daily caloric requirement by the amount wasted in nonproductive metabolic conversions [Specific Dynamic Action (SDA)]. Thus, out of an average daily consumption of $1.6 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$ (6 met), one-fourth, or 1.5 met, might constitute SDA (Brody, 1945). If this SDA were spread throughout the day, it would raise the minimum rate to the observed M_b of 2.5 met. In other words, we would postulate that the SDA is not expended in a metabolic bulge following the meal as in other carnivores but rather is rationed out over the day. We have no information as to how this might be effected. Delayed absorption from the gut would meet the requirements but is hardly compatible with observations of food, including undigested flesh passing within 3 hr (Stullken and Kirkpatrick, 1955).

*The term "standard metabolism" usefully designates the mean basal level for mammals of different size according to the function $M/W = 3.8W^{-0.75}$, or $M = 3.8W^{0.25}$, where M is in $\text{cm}^3 \text{ O}_2/\text{hr}$ and W is in grams (Brody, 1945). Basal or other metabolic values are conveniently expressed as multiples of this standard rate (designated "met"), a unit that is thus independent of size.

Fig. 2.—Representative metabolic experiment in air showing activity cycles and stimulation by He-O_2 (4 : 1) (φ No. 9, 13.6 kg at -12°C).

Fig. 3.—Sea otter minimum metabolic values in air, He-O_2 , and water. Symbols, average of three lowest values; points, lowest value. Horizontal solid line, all values (3 min) in air plus three resting in water; horizontal dashed line, six lowest values in air and water; horizontal dotted line, standard metabolism for an average 18-kg mammal. Diagonal lines show elevated metabolism in air ($\circ$), He-O_2 ($\odot$), and water ($\bullet$) in 13- to 16-kg animals.

It does seem that each of these species has a special problem in thermoregulation, the shrew because of its very small size and the sea otter because of its cold aquatic habitat. Indeed, were it not for their high M_b , their thermoneutral zones would be much more limited with critical temperatures above their normal T_a rather than below. The use of SDA, representing heat that must be produced and disposed of in any event, would allow thermoregulation by physical means rather than by chemical regulation.

Average Metabolism and Daily Energy Requirements

The M_{av} in air during ten 3- to 5-hr experiments in rather close confinement (Fig. 4) ranged from 20 to 54% above the M_b (average was $0.99 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$). In water, which allowed more freedom of movement, the average rate in 13 runs was higher, ranging from 25 to 125% above the M_b (average was $1.21 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$), and this may represent a lower maintenance level for sea otters in captivity. Sea otters are known for their

voracious appetite and substantial maintenance requirement. Thus Kenyon (1969) measured a consumption of 20 to 23% of the body weight of fish (0.89 kcal/g) per day. This is equivalent to some 1.5 to $1.8 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$, a value that corresponds well to our average of $1.4 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$ for three animals swimming at 5°C when one considers the constraint of our experimental format and the wastage of food during tank feeding.

Maximum Metabolism

Our greatest cold stress, -19°C in $\text{He}-\text{O}_2$, did not exceed the sea otter's metabolic capacity. This perhaps is not surprising since in subsequent experiments with mink (*Mustela vison*), a much smaller mustelid, we did not reach the limit of cold tolerance until -60°C in $\text{He}-\text{O}_2$. Although the sea otters were rather closely confined in their metabolism chambers, some individuals showed remarkable vigor in attacking the cage or tank lid to briefly sustain M_{max} as high as 2.8 and $2.6 \text{ cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1}$ in air and water, respectively.

Fig. 4—Sea otter average metabolic values in air (○), $\text{He}-\text{O}_2$ (◐), and water (●). Slopes of diagonals represent thermal conductances in $\text{cm}^3 \text{ O}_2 \text{ g}^{-1} \text{ hr}^{-1} \text{ } ^\circ\text{C}^{-1}$. Max. represents fur infiltrated with water.

This $M_{\max.}$ of 10 met is comparable to that found in mink (unpublished observations with K. Doi and L. Peyton) but is higher than values in rodents, which range from 5 to 8 met (Rosenmann and Morrison, 1974). However, in dogs, a species comparable in size to the sea otter, $M_{\max.}$ values near 25 met have been consistently reported in treadmill experiments (Young et al., 1959). This difference may relate to a more orderly mode of life in the sea otter without requirements for extreme exertion.

Thermal Conductance

Following Newton's law of cooling, the quotient of metabolism and the ambient-to-deep-body temperature differential ($T_b - T_a$) has been used to describe an overall "thermal conductance." Table 1 gives such values under different conditions in the sea otter. Since the lowest T_a (-19°C) did not raise the metabolism above M_b (i.e., was above the critical temperature), we can only say

Table 1—Thermal Metabolic Increments (Conductance) in Sea Otters

Mode*	Critical T_a , $^\circ\text{C}$	Conductance, $\text{cm}^3 \text{O}_2 \text{ g}^{-1} \text{ hr}^{-1} \text{ }^\circ\text{C}^{-1}$
$C_{\min.}^{\text{air}}$	< -19	< 0.012
$C_{\min.}^{\text{He}}$	5	0.023
$C_{\min.}^{\text{H}_2\text{O}}$	< 7	< 0.025
$C_{\max.}^{\text{air}}$	> 19	> 0.057
	$< 23^\dagger$	0.070
$C_{\max.}^{\text{H}_2\text{O}}$	25	0.084
$C_{\max.}^{\text{H}_2\text{O}'}$	> 33	> 0.165

*Superscripts indicate medium; subscripts indicate minimum or maximum limiting conductance; max.' designates conditions after infiltration of fur with water.

†Nonequilibrium experiment corrected for heat storage.

that the minimum conductance in air ($C_{\min.}^{\text{air}}$) was $< 0.012 \text{ cm}^3 \text{O}_2 \text{ g}^{-1} \text{ hr}^{-1} \text{ }^\circ\text{C}^{-1}$, a value that represents only fair insulation as compared to northern terrestrial mammals that bear longer fur. The sea otter's advantage, of course, lies in the resistance of its pelt to penetration by water (Table 2), which thus retains its integrity during immersion and active swimming. Thus $C_{\min.}^{\text{H}_2\text{O}}$ was $< 0.025 \text{ cm}^3 \text{O}_2 \text{ g}^{-1} \text{ hr}^{-1} \text{ }^\circ\text{C}^{-1}$, although we suspect that the M_b of $0.67 \text{ cm}^3 \text{O}_2 \text{ g}^{-1} \text{ hr}^{-1}$ might have maintained the animal at 0°C ($C_{\min.}^{\text{H}_2\text{O}}$ of 0.018). By comparison, we have found that immersion of the snowshoe hare (*Lepus americanus*) increased its conductance

Table 2—Conductance Ratios in Sea Otters*

Effect of medium	$C_{\min.}^{\text{He}}/C_{\min.}^{\text{air}} = > 1.9$ $C_{\min.}^{\text{H}_2\text{O}}/C_{\min.}^{\text{air}} = 2.1$ $C_{\max.}^{\text{H}_2\text{O}}/C_{\max.}^{\text{air}} = 1.3$
Range of adjustment	$C_{\max.}^{\text{air}}/C_{\min.}^{\text{air}} = > 4.8$ $C_{\max.}^{\text{H}_2\text{O}}/C_{\min.}^{\text{H}_2\text{O}} = > 3.4$ $C_{\max.}^{\text{H}_2\text{O}}/C_{\max.}^{\text{H}_2\text{O}'} = > 2.0$
Overall range	$C_{\max.}^{\text{H}_2\text{O}}/C_{\min.}^{\text{air}} = > 7.0$ $C_{\max.}^{\text{H}_2\text{O}}/C_{\min.}^{\text{H}_2\text{O}'} = > 13.8$

*Coding as in Table 1.

by some 10-fold. Thus the sea otter is maintained at close to its M_b even in icy water. Similarly in air the critical temperature lay below -20°C ; so actual environmental conditions on land (Armstrong, Chap. 4, this volume) should never require more than M_b for maintenance.

In contrast to air and water, the increased conductivity of He- O_2 provided conditions below thermal neutrality (critical T_a of 5°C) so that a valid estimate of $C_{\min.}^{\text{He}} = 0.023 \text{ cm}^3 \text{O}_2 \text{ g}^{-1} \text{ hr}^{-1} \text{ }^\circ\text{C}^{-1}$ for 12- to 14-kg individuals could be made for this medium (Fig. 4). This facilitation of heat flow by He- O_2 in the sea otters (> 1.9 -fold) was slightly greater than the 1.7-fold in the mink (unpublished observations with K. Doi and L. Peyton).

At higher T_a thermal conductance becomes limiting for the dissipation of heat rather than for its retention. Values for $C_{\max.}$ are estimated from average metabolism for each T_a . In the warmest equilibrium experiment (T_a of 19°C), $C_{\max.}^{\text{air}}$ was $0.057 \text{ cm}^3 \text{O}_2 \text{ g}^{-1} \text{ hr}^{-1} \text{ }^\circ\text{C}^{-1}$. In a nonequilibrium experiment at T_a of 22.5°C , which resulted in heat death, a slightly higher value of $0.070 \text{ cm}^3 \text{O}_2 \text{ g}^{-1} \text{ hr}^{-1} \text{ }^\circ\text{C}^{-1}$ was calculated with correction for heat storage. In warm water ($> 28^\circ\text{C}$) the animals showed a progressive loss of buoyancy until only the head stayed above the surface, which indicated that water had penetrated the fur. This afforded no inconvenience to the animals in which relaxed behavior and even sleep was observed and clearly facilitated heat transfer during the exposure. Under these conditions $C_{\max.}^{\text{H}_2\text{O}'}$ was $0.165 \text{ cm}^3 \text{O}_2 \text{ g}^{-1} \text{ hr}^{-1} \text{ }^\circ\text{C}^{-1}$ whereas at T_a of 25°C with buoyancy retained, $C_{\max.}^{\text{H}_2\text{O}}$ was only $0.084 \text{ cm}^3 \text{O}_2 \text{ g}^{-1} \text{ hr}^{-1} \text{ }^\circ\text{C}^{-1}$.

As overall conductance is increased at higher T_a , heat must be lost from the large flat paws that have an admirable conformation for such dispersal (Table 2). If the integrity of the fur is maintained,

more than two-thirds of the heat load must go through the paws in water at 26°C and perhaps four-fifths in air at 22°C. At 28°C and above, survival appears only possible because of the infiltration of water into the fur with a twofold further increase in conductance, the highest values observed being 7 times the minimum value in water and 14 times that in air. We have subsequently observed a similar tolerance in young harbor seals (Miller et al., 1976).

Body Temperature

The range of values found in some 50 measurements, including exposure to heat and cold and several conditions of confinement, is shown in Fig. 5. A mean T_b of 38.1°C was measured in animals removed directly from the holding pool or

Fig. 5.—Body temperatures in sea otters. Previous confinement in metabolic chamber under different thermal conditions: Cold, Neutral, Warm, and Lethal. Symbols represent animals measured directly from the pool (○), after transport inside holding box (◐), and after drying by fan inside holding cage (●). (See Table 3.)

Table 3—Body Temperatures in Sea Otters According to Previous Condition

Holding pool		T_b ,* °C	Metabolism chamber	
Condition	SD (No.)		SD (No.)	Condition
Via cage (dried)	0.45(6)†	44.1	(1)	Air 23
		38.5	0.13(7)‡	Air 14 → 19
				H ₂ O 25 → 33
Via box	0.37(10)§	38.3		
Direct	0.42(7)	38.1	0.25(6)	Air -10 → 12
				H ₂ O 5 → 25
		36.7	0.45(8)‡	Air < -10

*These averages exclude animal No. 7, a grizzled female estimated as the oldest of the group at 6 to 7 years. All her T_b values lay below the range of the other seven individuals and >4σ below their mean.

†Confinement in screen holding cage with fan to dry fur for 20 to 30 min; significant vs. direct at 5% level.

‡Significant vs. direct at 1% level.

§Confinement in wooden weighing box for 10 to 15 min; not significant vs. direct.

after confinement during a metabolic experiment at neutral T_a (Table 3). Since both circumstances include some undefined activity and since these values represent daytime levels in a diurnal species, the basal level may be lower. This average value of 38.1°C under neutral and quiet conditions corresponds to that of 37.9°C by Stullken and Kirkpatrick (1955) on two Nembutalized captives. These values fall below resting levels for smaller mustelids (*Mustela* sp.) but are comparable to those from some genera (*Mephitis* and *Taxidea*) (Morrison and Ryser, 1976). This also corresponds to an overall average of 37.8°C for "all" mammals (Morrison and Ryser, 1952), although a trend toward slightly lower T_b in aquatic mammals as compared to their terrestrial relatives has been noted (Morrison, 1962). Stullken and Kirkpatrick's values on six individuals killed in the field varied widely from 35.0 to 40.8°C and may reflect some range of prior activity. However, three middle values (37.5 to 37.8°C) may represent natural inactivity.

Confinement before a metabolism experiment resulted in small (0.4°C) T_b increases (Table 3), as did warm exposure during metabolism experiments (25 to 33°C in water and 12 to 19°C in air). Irving and Krog's (1954) value on a captured sea otter is the same as our average of 38.5°C for confined (excited) subjects or ones under warm conditions. The regularity of these values (Table 3) suggests a rather effective control and cooling mechanism for heat regulation.

The one experiment carried to lethal hyperthermia demonstrated the wide thermal margin of 6°C available to this species. Moreover, the devel-

oping stages and even the final critical T_b level did not appear to impair the animal since full vigor was maintained with $M_{\max.} > 8$ met. This individual maintained a state of excitement throughout the 2-hr exposure at 22.5°C, with an average metabolic rate of 1.85 cm³ O₂ g⁻¹ hr⁻¹. If all the heat produced (~3.5 cm³ O₂/g) had been retained, the temperature would have increased some 20°C rather than 5°C; so three-fourths of the heat load was successfully dissipated. Clearly the avoidance of maladaptive behavior (vigorous activity) would have allowed survival, and another individual accepted a 3-hr exposure at 19°C with an average rate of 1.10 cm³ O₂ g⁻¹ hr⁻¹ and no T_b increase beyond the normal range.

The T_b response to cold showed greater displacement averaging -1.4°C with considerable scatter. The conditions at -5 to -20°C in He-O₂ were severe, being roughly equivalent to -40 to -70°C in air. However, the low T_b values appeared to be maintained, with no correlation with duration of exposure or with some range of T_a . Neither did the metabolism values show any progressive decline. Thus, although not so precise, regulation to cold was very effective even at T_a below -40°C. Certainly these individuals as maintained under optimal conditions did not confirm Stullken and Kirkpatrick's (1955) impression of the sea otter as a poor thermoregulator.

The tolerance of very warm water was an unexpected finding in view of the normal habitat of these animals, which must only rarely exceed 5°C. Still the range of this species (as *Enhydra lutris nereis*?) (Hall and Kelson, 1959) extended as far south as Baja California, and so it is of much interest that even the northern populations have the physiological flexibility to tolerate the waters of a sun-warmed subtropical lagoon.

SUMMARY

The sea otter has a unique configuration for thermoregulation in terms of its size, aquatic mode, and habitat in the cold but constant Bering Sea. In ten 13- to 33-kg individuals captured and maintained at Amchitka Island under near natural conditions at Constantine Harbor, a basal metabolic level of 0.72 cm³ O₂ g⁻¹ hr⁻¹ was found in 17 values measured over thermoneutral zones of -20 to 21°C in air and 20 to 33°C in water. This level, more than 2.5 times the standard (average basal) level for a mammal of this size, is unique among mustelids but conforms to the pattern seen in marine mammals from other orders. Average values of 1.0 to 1.2 cm³ O₂ g⁻¹ hr⁻¹ and maximum values of 1.9 and 2.6 cm³ O₂ g⁻¹ hr⁻¹ in air and water, respectively, confirm the high food demand

of one-fifth to one-fourth their body weight in fish daily. Thermal conductance in air, <0.012 cm³ O₂ g⁻¹ hr⁻¹ °C⁻¹, was greater for these mammals than for terrestrial arctic mammals, but it only increased twofold on immersion in water. Water infiltration into the fur at higher temperatures allowed survival at even 33°C, perhaps significant in the far southern distribution of the species. Body temperature was regulated under neutral conditions at 38.1 ± 0.34°C (mean ± standard deviation), under cold conditions at 36.7 ± 0.45°C, and under warm conditions at 38.5 ± 0.31 with 44.1°C as a single lethal value. These observations provide new bioenergetic insights and may allow improved techniques for holding and shipping these remarkable creatures both for transplantation to new habitats and as favored attractions in exhibition of animals.

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Radionuclides in Air, Water, and Biota

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Air, water, and biological samples collected before and after the 1965, 1969, and 1971 underground nuclear detonations at Amchitka Island were analyzed for natural and fallout radionuclides by gamma spectrometry. Selected samples were also analyzed for tritium, ^{55}Fe , and ^{90}Sr . The objectives were to search for and identify radionuclides of Amchitka origin in the samples and to contribute to the general knowledge of the distribution of radionuclides in the environment. The collection of seafoods and the analyses of samples for radionuclides potentially available to man through the food web were emphasized, but other organisms were also analyzed in the search for radionuclide indicator species. The identification of the origin of the fallout radionuclides in the samples required accurate measurement of the radionuclides in both the preevent and postevent samples since some fallout radionuclides were present at Amchitka before the 1965 event and other fallout radionuclides arrived during the 11-year period of study.

The samples were principally collected in areas likely to be contaminated if any seepage of radionuclides from the site of the underground detonations occurred. Of the 81 types of organisms analyzed, 37 were vertebrates (2 mammals, 22 fish, and 13 birds), 20 were invertebrates, 11 were marine algae, 4 were freshwater plants, and 9 were land plants; several thousand were analyzed. The results have been published in several reports, including a series of six progress reports for the years 1970 to 1975.

The studies showed that there has been no escape of radionuclides from the underground sites of the three nuclear detonations at Amchitka Island except for trace quantities of radionuclides, principally tritium, in water and soil gas samples from the immediate vicinity of the surface ground zero for the 1965 event. Two naturally occurring radionuclides, ^{40}K and ^7Be , were the most abundant radionuclides in the samples, usually by a factor of 10 or more, except for ^{137}Cs in lichen samples. All levels were well below applicable Radiation Protection Guides, often being near the statistical limit of detection.

The underground nuclear detonations at each of three locations on Amchitka Island were designed to retain in the immediate vicinity of the detonation all the radionuclides that were produced. Air, water, and biological samples collected before and after each of the detonations were analyzed for their radionuclide content to determine if this goal was achieved. Some naturally occurring and worldwide fallout radionuclides were present on Amchitka Island before the first Amchitka nuclear detonation, and some fallout of radionuclides from nuclear detonations elsewhere occurred during the period of study. Therefore the objectives of the program were to search for radionuclides of Amchitka origin in the environment and to advance general knowledge about the environmental distribution of radionuclides. The collection of seafoods and the analyses for radionuclides potentially available to man through the food web were emphasized, but other organisms were collected and analyzed to obtain clues about the origin of radionuclides at Amchitka and to identify indicator species, species that significantly concentrate

one or more of the radionuclides present at Amchitka.

Radioecological surveys were made for each of the three underground nuclear detonations on Amchitka, Long Shot (1965), Milrow (1969), and Cannikin (1971). Information about the three events and references to event-related radioecological surveys are given in Table 1.

The program in 1965 included observation and radiometric analyses of samples collected during the period from 2 weeks before until 4 days after the Long Shot detonation. In a series of nuclear detonations, a postevent survey for one detonation is a preevent survey for the following detonation. In this sense the limited post-Long Shot observations were a part of the pre-Milrow survey, but more intensive surveys for Milrow began in 1967. Likewise, the immediate post-Milrow survey data supplemented the information obtained from the pre-Cannikin surveys that began in July 1970. The post-Cannikin surveys began immediately after the November 1971 detonation and have continued periodically since. At present (1976) the program

Table 1—Schedule of Amchitka Underground Nuclear Detonations and References to Reports of Event-Related Radioecological Surveys

Event	Date	Yield, kt	Depth, m	References
Long Shot	Oct. 29, 1965	80	710	Seymour and Nakatani, 1967 Koranda et al., 1967
Milrow	Oct. 2, 1969	~1000	1219	Isakson and Seymour, 1968 Vogt et al., 1968 Koranda et al., 1969 Merritt, 1970
Cannikin	Nov. 6, 1971	~5000	1791	Held, 1971 Held, 1972 Held et al., 1973 Merritt, 1973 Nelson and Seymour, 1974 Nelson and Seymour, 1975 Nelson, 1975 Nelson and Seymour, 1976

has been reduced to a single field survey and collection per year.

In addition, the U. S. Environmental Protection Agency (EPA) conducted an extensive offsite monitoring program throughout the Aleutian Island chain and in mainland Alaska. Also, there has been a program since 1965 for the collection and analysis of groundwater and surface-water samples for tritium (^3H) by the U. S. Geological Survey, Teledyne Isotopes, Inc., EPA's National Environmental Research Center (NERC), Las Vegas, and the Lawrence Radiation Laboratory (now Lawrence Livermore Laboratory). The reports by Ballance (1974), Essington (1971), Fort and Wruble (1972), and Koranda, Martin, and Wikerink (1967) are representative of the work performed by these groups. The collection and analysis of samples for ^3H by the Laboratory of Radiation Ecology began in 1970.

The program for the collection and analyses of samples was designed on the expectation that the amounts of radionuclides in the samples would be only slightly greater than the existing low levels of background radiation from natural and man-made sources. Hence large samples and sensitive radiation detection and measurement systems were required. The two categories of radionuclides that contribute to background radiation are (1) natural and (2) artificial.

The natural radionuclides are either of terrestrial or atmospheric origin. Those of terrestrial origin are residual radionuclides from the time of the earth's formation and hence are of long half-life, whereas those of atmospheric origin are constantly being produced by the interaction of cosmic radiation with nuclei of gases in the atmosphere. Potassium-40 is the most abundant

radionuclide of terrestrial origin in biological samples, and, generally, it is present in amounts that range from a few to many times greater than all other radionuclides, natural or artificial. As examples of the distribution of ^{40}K , levels in muscle of marine fish from Amchitka ranged from 9 to 20 pCi/g of dry tissue; levels in a sample of *Alaria*, a marine algae, were 80 pCi/g of dry weight. In seawater there are about 0.32 pCi/g, and in the whole body of an 80-kg man, about 140,000 pCi, which is equivalent to 1.75 pCi/g of wet weight. Other radionuclides of terrestrial origin that may or may not be present in detectable quantities are ^{87}Rb and isotopes of thorium and uranium and their daughter nuclides.

The most common natural radionuclides of atmospheric origin are ^3H , ^{14}C , and ^7Be . These radionuclides are produced by the interaction of cosmic-ray particles with nuclei of nitrogen atoms in the atmosphere. However, not all the ^3H and ^{14}C in the environment is of natural origin since these two radionuclides are also produced in significant amounts by nuclear detonations. After the 1961 and 1962 atmospheric test series by the Union of Soviet Socialist Republics and the United States of America, the earth's reservoir of ^3H was increased by nearly 500% and of ^{14}C by 10 to 15% (Schell, Sauzay, and Payne, 1974). The present level of ^3H in rainwater ranges from about 0.1 to 1 pCi/g of water (Schell et al., 1974). Without input from nuclear detonations, the reservoir of ^3H will decrease relatively rapidly since its radiological half-life is 12.3 years.

Carbon-14 produced in the atmosphere combines with oxygen to form a CO_2 molecule that becomes immediately available to terrestrial plants and somewhat later, owing to holdup at the

air–water interface, to aquatic plants. The concentration of ^{14}C in contemporary terrestrial plants is 6.11 pCi (13.56 dpm) per gram of carbon (Karlen et al., 1964). Any changes in the reservoir of environmental ^{14}C , such as those which occurred in 1961 and 1962 from nuclear testing, will persist for a long period of time because of the long radiological half-life of ^{14}C , 5730 years.

The third radionuclide produced in the atmosphere that is detectable in some samples, especially lichens and freshwater plants, is ^7Be . Maximum values for this radionuclide in Amchitka organisms are less than 5 pCi/g of wet sample and 0.3 pCi/g for water (Nelson and Seymour, 1975). (On a dry-weight basis, a maximum value of 37 pCi/g for *Ranunculus*, a freshwater plant, was observed.)

The other sources of background radiation are the fallout radionuclides—fission products, induced radionuclides, and unused parent materials from the nuclear devices. Fallout radionuclides in the troposphere reach the earth's surface in a few days to a few months, but a few months to a few years are required for radionuclides that are injected into the stratosphere to return to the earth's surface. Amchitka, at 51°N 179°E , is at a latitude where fallout would be expected to be at a maximum both for tropospheric fallout from detonations at the Lop Nor test site in China and for stratospheric fallout that reaches the earth through the break in the tropopause in the northern hemisphere. No tropospheric and little, if any, stratospheric fallout from the French nuclear detonations in the South Pacific, 22°S , would be expected at Amchitka Island. The rate of fallout on Amchitka, although small, may have varied severalfold within a year during the period of study because of fresh tropospheric fallout from nuclear detonations at Lop Nor and the usual seasonal changes in stratospheric fallout. This accounts for much of the variability in radionuclide values that has been observed for samples of the same species collected at different seasons of the year. However, some of the variability in radionuclide values is also due to ecological and biological factors that affect the metabolic rate of organisms.

Any new contributions of small quantities of fresh-fallout radionuclides to Amchitka would be difficult to detect. A large increase in environmental radioactivity at Amchitka only would obviously point to a local source of contamination, but a small increase could be attributed either to a local source of radioactivity or to worldwide fallout. Since the radionuclides in fallout are the same as those produced by the Amchitka detonations, there is no direct means of identifying the origin of the radionuclides by the presence of

specific radionuclides in the samples. One indirect means of identifying their origin would be to compare the amounts and kinds of radionuclides in Amchitka samples with radionuclides in samples from distant areas. A second means would be to compare a calculated date of origin of the radionuclides in the samples with the dates of the Amchitka detonations. The date of origin can be readily calculated from the ratio of a radioactive parent to a radioactive daughter in the sample if the half-lives of the two radionuclides are significantly different and relatively short and if no fractionation of parent and daughter by either physical or biological processes has occurred.

SAMPLE COLLECTION

The number of samples collected was a compromise between the need to know about the kinds and amounts of radionuclides in as many types of samples as possible and recognition that only a finite number of samples could be analyzed. For this reason the highest priority was given to the collection of samples that would provide information on the transfer of radionuclides from the ocean to man. Organisms of special interest were fish and crabs from Amchitka and salmon from Alaska canneries as well as organisms in trophic levels immediately below seafoods. Other organisms were also collected and analyzed in a search for indicator species, species which significantly concentrate one or more radionuclides and which are readily available in quantities sufficient to provide adequate amounts of samples without significantly affecting the population of the species in the collection area.

Samples were collected from offshore and intertidal areas, freshwater streams and ponds, and terrestrial areas. At the offshore stations on both the Pacific Ocean and Bering Sea sides of Amchitka Island, fish and water samples were collected by the *M. V. Commander*, and in situ measurements of radioactivity in seawater were made with a gamma probe operated from the *M. V. Pacific Apollo* (Held, 1972). The sample collection stations, both offshore and intertidal, where appropriate, were the same stations that were selected by the Fisheries Research Institute, University of Washington, for their ecological studies. Stations on the island proper were selected either as sites that were most likely to be contaminated if radionuclides escaped from the underground detonations or sites that were unlikely to be contaminated, i.e., control areas; hence the sample collection stations were either near or some distance from the ground zero areas. The three detonations

were within 8 km of each other and in the southeastern part of the island, as shown on the Geological Survey map in the pocket at the back of this volume. Landmarks and the locations of collection stations near the ground zero areas are shown in Figs. 1 (Long Shot), 2 (Milrow and Long Shot), and 3 (Cannikin).

fish muscle, 4.3; king crab muscle, 6.6; plankton, 21; noncoralline marine algae, 6.3; freshwater plants, 7.4; and lichens, 3.8.

In addition to the biological samples, air and water samples were collected and analyzed to determine the amounts and kinds of radionuclides available to the biota and to signal the arrival of

Fig. 1—Collection sites and other prominent features in the vicinity of Long Shot ground zero.

Of the 81 types of biological samples collected for analyses, 37 were vertebrates (2 mammals, 22 fish, and 13 birds), 20 were invertebrates, 11 were marine algae, 4 were freshwater plants, and 9 were land plants. Their scientific and common names are given in Table 2.

The radioactivity values have been reported most frequently in terms of dry weight because accurate wet weights are difficult to determine routinely for some organisms, such as mussels, algae, aufwuchs, and plankton. Held (1971) prepared a table of approximately 100 wet-dry weight ratios based on a limited number of carefully determined wet and dry weights. Representative values from this list are as follows:

radionuclides at Amchitka from other areas. The presence of fresh or unexpected radionuclides in air or water samples could herald the arrival of either tropospheric or stratospheric fallout from nuclear detonations elsewhere in the northern hemisphere.

Most of the samples were collected with conventional instruments, but the water sampler, the air sampler, and the in situ detector for measurement of radioactivity in seawater have unique features that need description for proper interpretation of results. The measurement of trace amounts of radionuclides or chemical elements in water frequently depends on the collection and transport of large quantities of water in toto from

Fig. 2—Collection sites and other prominent features in the Long Shot and Milrow areas.

the field to the home laboratory for analysis. To simplify the problems of collection and transport, Battelle Northwest Laboratories developed a water sampler that permits the collection of particulates on a filter and of charged ions on a sorption bed. This sampler can process a large volume of water in the field in a relatively short period of time, and only the filter papers and the sorption beds need to be returned to the laboratory for analyses. The essential components of the sampler are a pump, six to eight 0.3- μm Millipore filters arranged in parallel, and one to three aluminum oxide (Al_2O_3) sorption beds arranged in series. The Al_2O_3 bed sorbs both anions and cations but has a limited holding capacity for some ions; this bed also is an efficient collector of colloids.

The air samplers used by the Laboratory of Radiation Ecology (LRE) in the late post-Cannikin

period were the same samplers used by Eberline Instrument Company during the pre-Cannikin and immediate post-Cannikin surveys. The essential components of the sampler are a Gast positive displacement pump, calibrated at 10 ft^3/min , and a 15-cm filter head lined with No. 41 Whatman filter paper. For the late post-Cannikin period, three units were operated continuously from Feb. 23, 1972, to Aug. 28, 1973, in a shed near the main camp but away from potential sources of contamination. Air particulates were collected on No. 41 Whatman filter paper, but the charcoal filter was not used. Since closure of the camp in September 1973, only an 8-day sample in August–September 1974 has been collected.

The in situ probe for measurement of gamma-emitting radionuclides in seawater is essentially a 5-by 5-in. sodium iodide detector with a photomulti-

Fig. 3—Collection sites and other prominent features in the Cannikin area.

plier tube and a preamplifier and a linear amplifier enclosed in a pressure-resistant case for use in deep water (Riel, 1966). The probe was tested and calibrated aboard the M.V. *Pacific Apollo* at Amchitka in August 1971 and later used at four locations in the Bering Sea near C Site on the day after the Cannikin event. No gamma radionuclides were detected other than naturally occurring ^{40}K . The limit of detection for a 1-hr counting period was approximately 1 pCi of ^{95}Zr per liter of seawater.

SAMPLE ANALYSES

The samples were analyzed for gamma-emitting radionuclides, ^3H , ^{55}Fe , ^{90}Sr , and plutonium, with most of the effort at LRE being spent on the analyses for gamma-emitting radionuclides by gamma-ray spectrometry. Two systems were used.

The principal components for one were a 3- by 3-in. sodium iodide crystal detector (NaI) and a 200-channel pulse-height analyzer and for the other a germanium lithium-drifted diode detector [Ge(Li)] and a 4096-channel pulse-height analyzer. If the radionuclides in the samples were not satisfactorily identified by the NaI system, the samples were then analyzed by the Ge(Li) system, which has a higher degree of resolution for gamma energies than the NaI system. For example, the three gamma photons emitted by ^{95}Zr – ^{95}Nb (724, 756, and 765 keV) appear as a single peak on the NaI spectrum but as three peaks on the Ge(Li) spectrum.

Analysis for tritium in water requires distillation of either free or extracted water and measurement of ^3H in the distilled water by liquid scintillation detection methods (Held et al., 1973). Since a system for measuring tritium in tissue-

Table 2—Common and Scientific Names of Organisms Collected for Radiological Analyses

Common name		Scientific name	Common name		Scientific name
Vertebrates			Invertebrates (Continued)		
Mammals	Otter, sea	<i>Enhydra lutris</i>	Crab		
	Rat	<i>Rattus norvegicus</i>	False king		<i>Lithodes aequispina</i>
Fish	Cod, Pacific	<i>Gadus macrocephalus</i>	Horse		<i>Erimacrus isenbeckii</i>
	Dolly Varden	<i>Salvelinus malma</i>	King		<i>Paralithodes camtschatica</i>
	Flounder, arrowtooth	<i>Atheresthes stomias</i>	Tanner		<i>Chionoecetes tanneri</i>
	Greenling, rock	<i>Hexagrammos lagocephalus</i>	Isopod		<i>Idotea wosnesenskii</i>
	Halibut, Pacific	<i>Hippoglossus stenolepis</i>	Krill		Euphausiids
	Lampfish, northern	<i>Stenobranchius leucopsarus</i>	Medusa		<i>Cyanea</i> sp.
	Lantern fish		Medusa		<i>Aurellia</i> sp.
	Mackerel, Atka	<i>Pleurogrammus monopterygius</i>	Mussel		<i>Mytilus edulis</i>
		<i>Sebastes alutus</i>	Mysids		<i>Acanthomysis</i> sp.
	Perch, Pacific ocean		Octopus		<i>Octopus</i> sp.
	Pollock, walleye:		Plankton		spp.
	whiting; Alaska	<i>Theragra chalcogramma</i>	Scallop		<i>Pecten hericeus</i>
	Rattail	<i>Coryphaenoides acrolepis</i>	Snail		<i>Littorina</i> sp.
	Red Irish lord	<i>Hemilepidotus hemilepidotus</i>	Snail		<i>Thais lima</i>
	Rockfish, dusky	<i>Sebastes ciliatus</i>	Sponge		<i>Halichondria</i> sp.
	Salmon		Squid, pelagic		<i>Gonatus</i> sp.
	Chinook; king	<i>Oncorhynchus tshawytscha</i>	Urchin, green sea		<i>Strongylocentrotus polyacanthus</i>
	Chum	<i>Oncorhynchus keta</i>	Marine Algae		
	Coho; silver	<i>Oncorhynchus kisutch</i>	Algae, coralline		<i>Corallina</i> sp.
	Pink	<i>Oncorhynchus gorbusha</i>	Seaweed		<i>Alaria crispa</i>
	Sockeye	<i>Oncorhynchus nerka</i>	Seaweed		<i>Constantinea rosa-marina</i>
	Sculpin	Cottidae	Seaweed		<i>Fucus distichus</i>
	Smelt, deep sea;		Seaweed		<i>Hedophyllum sessile</i>
	California		Seaweed		<i>Halosaccion glandiforme</i>
	smoothtongue	<i>Bathylagus stibius</i>	Seaweed		<i>Hypophyllum dentatum</i> or <i>ruprechtianum</i>
	Sole, rock	<i>Lepidopsetta bilineata</i>	Seaweed		<i>Laminaria longipes</i>
	Stickleback, threespine	<i>Gasterosteus aculeatus</i>	Seaweed		<i>Porphyra</i> spp.
			Seaweed		<i>Thalassophyllum clathrus</i>
			Seaweed		<i>Ulva lactuca</i>
Invertebrates			Freshwater Plants		
Birds	Auklet		Algae, filamentous		<i>Cladophora</i> sp.
	Least	<i>Aethia pusilla</i>	Aufwuchs, periphyton, and other organisms		
	Parakeet	<i>Cyclorhynchus psittacula</i>	Moss		<i>Fontinalis neomexicana</i>
	Goose, Emperor	<i>Philacte canagica</i>	Ranunculus, crowfoot		<i>Ranunculus</i> sp.
	Guillemot, Pigeon	<i>Cephus columba</i>	Land Plants		
	Gull, Glaucous-winged	<i>Larus glaucescens</i>	Crowberry		<i>Empetrum nigrum</i>
	Murre, Thick-billed	<i>Uria lomvia</i>	Clover, white		<i>Trifolium repens</i>
	Oystercatcher, Black	<i>Haematopus bachmani</i>	Grass		<i>Agrostis</i> sp.
	Ptarmigan, Rock	<i>Lagopus mutus</i>	Grass		<i>Calamagrostis nutkaensis</i>
	Puffin, Tufted	<i>Lunda cirrhata</i>	Lichen		<i>Cladonia</i> sp.
	Sandpiper, Rock	<i>Calidris ptilocnemis</i>	Lupine		<i>Lupinus nootkatensis</i>
	Teal, Green-winged	<i>Anas crecca</i>	Moss		
	Tern, Arctic	<i>Sterna paradisaea</i>	Rye, wild		<i>Elymus arenarius mollis</i>
	Wren, Winter	<i>Troglodytes troglodytes</i>	Sedge		<i>Carex</i> sp.
	Amphipod, sand flea	<i>Gammarus</i> sp.			
	Basket star	<i>Gorgonocephalus caryi</i>			

bound hydrogen (TBH) of plants and animals has just been completed and tested, only preliminary results are available at this time. The system makes use of a combustion chamber to extract the tissue-bound water and an azeotropic distillation process to purify the extracted water (Nelson and Seymour, 1975).

Iron-55 decays by electron capture and is detected by the X ray that is produced indirectly

in the decay process. The measurement of ^{55}Fe requires chemical separation and deposition of the extracted iron on a planchette and the use of a thin crystal for spectrometric detection of the X ray.

Strontium-90 decays entirely by beta emission and can be measured most reliably by the measurement of its radioactive daughter, ^{90}Y . The procedure is to chemically extract strontium from the sample, set the extracted sample aside for 2 weeks

to allow the radioactive decay of ^{90}Sr and ^{90}Y to reach equilibrium, and then separate and beta count the ^{90}Y .

Plutonium is extracted from the samples by ion exchange, electroplated on platinum disks, and analyzed by an alpha spectrometry system that includes surface-barrier detectors and a pulse-height analyzer. For the determination of the chemical yield, ^{242}Pu is used as a tracer.

The limits of detection of the gamma systems for each of the radionuclides were an important factor in the consideration of the error terms for the values of the radionuclides because the amounts of radionuclides in the samples were often near the limit of detection. Many factors influence the limit of detection, including the type of detector and analyzer, the presence of other radionuclides, the duration of the counting period, the size and density of the sample, and the geometry relationship of the sample and detector. Hence the limits of detection varied considerably for various radionuclides and types of samples but can be summarized by stating that the detection limits were approximately as follows:

By gamma detection	
^{40}K	2.1 pCi/g or less
^7Be , ^{103}Ru , ^{144}Ce	
^{228}Th , ^{238}U	0.41 pCi/g or less
^{95}Nb , ^{95}Zr , ^{125}Sb , ^{137}Cs , ^{155}Eu , ^{226}Ra	0.12 pCi/g or less
By beta detection	
^3H	<48 pCi/liter
^{90}Sr	<0.04 pCi/g
By X-ray detection	
^{55}Fe	<0.04 pCi/g
By alpha detection	
$^{239,240}\text{Pu}$	<0.005 pCi/g

RESULTS

Detailed results of radiometric analyses of Amchitka samples are given in the LRE Long Shot, Milrow, and Cannikin progress reports (Table 1). The effort expended on the radiobiological programs has been much greater for Cannikin than for the other two programs, and, since each Cannikin progress report summarizes data from previous reports as well as presents the results of current analyses, the most recent progress report (1976) is the best single source of radiobiological information. For this reason tables from recent progress reports (Nelson and Seymour, 1975; 1976) are included in this report as Tables A.1 to A.20 of the appendix.

The long-term trends of the radionuclide values for various sample types for the period 1965 to

Fig. 4—Cesium-137 and ^{40}K in seaweed, Dolly Varden muscle, and lichens for the period 1965 to 1975.

Fig. 5—Cesium-137 in the freshwater moss, *Fontinalis* sp., from six locations, 1970 to 1975.

1975 are given in Figs. 4 to 7 and Table 3. In these figures and tables, data have been averaged for selected time periods, usually 1 year. Figure 4 shows the relationship between a naturally occurring radionuclide (^{40}K) and a long-lived fallout radionuclide (^{137}Cs) for a biological indicator species from each of three environments. The data in Fig. 5 for one radionuclide (^{137}Cs) and one sample type (freshwater moss) from each of six areas demonstrate area effect. In Fig. 6 the four

Fig. 6—Selected fallout radionuclides in lichens for the period 1965 to 1975.

most abundant fallout radionuclides (^{137}Cs , ^{144}Ce , ^{106}Ru , and ^{125}Sb) are quantitatively related to the sample type (lichens) in which they occur in greatest concentrations. The values for the amount of ^3H in samples of water from Long Shot Mud Pit No. 1, other freshwater sources, and the ocean are given in Fig. 7. For an evaluation of the amount of radioactivity in the most likely pathways for the transfer of radionuclides from the Amchitka environment to man, the results of analyses of fish, crab, and a game bird for the most abundant naturally occurring and fallout radionuclides are given in Table 3.

Fig. 7—Mean tritium concentrations in water samples from Long Shot Mud Pit No. 1, other freshwater sources, and the ocean, 1965 to 1975.

DISCUSSION

Introduction

The values for the fallout radionuclides were often near or below the limits of detection, and the error terms for the values were large. Often the coefficient of variation (standard deviation $\div$ mean) exceeded 100%. The small values and relatively large error terms for the fallout radionuclides did not obscure the answer to the question about the presence or absence of radionuclides of Amchitka origin in the samples, the primary objective of the program; however, the Amchitka radiobiological data did not contribute significant new information about the cycling, concentration, and transfer of fallout radionuclides in the environment, which was the secondary objective.

A concise interpretation of the results of radiometric analyses of many hundreds of Amchitka samples collected over an 11-year period requires some screening of the data and, ultimately, limiting the principal discussion to a few significant sample types for a few radionuclides. Two variables considered in the process of selecting and reducing data were the time and the area of collection.

Table 3—Potassium-40, ^{55}Fe , and ^{137}Cs Concentration in Muscle of Fish, Crab, and Ptarmigan Collected at Amchitka Island from 1965 to 1975

Sample type	Year	^{40}K , pCi/g of dry weight			^{55}Fe , pCi/g of dry weight			^{137}Cs , pCi/g of dry weight		
		Range	$\bar{x} \pm \text{SD}$	n*	Range	$\bar{x} \pm \text{SD}$	n*	Range	$\bar{x} \pm \text{SD}$	n*
Salmon	1965		11.6	1/5		Na†			0.13	1/5
	1967	12–13	13 ± 0.6	2/22		Na		Ns†–0.11	0.06 ± 0.08	2/22
	1969	10–15	12 ± 1.7	14/14	0.6–9.7	2.2 ± 2.3	15/30	Ns–0.14	0.06 ± 0.03	14/14
	1971	8–15	12 ± 1.9	29/29		Na		Ns–0.12	0.04 ± 0.03	29/29
	1972	11–21	14 ± 2.9	10/10	0.39–1.1	0.58 ± 0.24	6/6	Ns	Ns	10/10
	1973		Na			Na			Na	
	1974	15–15	15 ± 0.1	2/2	0.36–0.42	0.39 ± 0.4	2/2	Ns–0.09	0.05 ± 0.06	2/2
Dolly Varden	1965	13–13	13 ± 0.3	2/41		Na		2.2–2.3	2.3 ± 0.11	2/41
	1969	3–13	12 ± 3.7	9/9	Ns–0.65	0.19 ± 0.19	11/11	Ns–1.8	0.50 ± 0.70	9/9
	1970	13–14	14 ± 0.7	2/22	1.6–1.6	1.6 ± 0.1	2/22	0.29–0.34	0.32 ± 0.04	2/22
	1971		15 ± 0.8	1/1		Na			0.35 ± 0.05	1/1
	1972	15–17	16 ± 1.0	3/8	0.23–0.49	0.36 ± 0.18	2/2	1.1–8.2	5.7 ± 3.9	3/8
	1973	15–16	16 ± 0.6	3/7		0.05 ± 0.01	1/4	0.13–0.28	0.18 ± 0.09	3/7
	1974	13–17	14 ± 1.6	6/28	Ns–0.09	0.06 ± 0.03	4/19	0.17–0.35	0.24 ± 0.08	6/28
	1975	4–16	12 ± 4.4	5/19		Na		0.05–0.33	0.17 ± 0.12	5/19
Halibut	1967	15–16	15 ± 0.6	2/2		Na		Ns–0.12	0.06 ± 0.08	2/2
	1969	11–18	14 ± 2.9	4/4		0.31	1/1	Ns–0.11	0.03 ± 0.06	4/4
	1970		20 ± 0.7	1/26		0.12	1/26		0.10 ± 0.05	1/26
	1971	16–20	19 ± 1.3	7/7		Na		Ns–0.19	0.07 ± 0.08	7/7
	1972	15–20	16 ± 1.4	7/7	0.35–0.36	0.36 ± 0.01	2/2	Ns–0.06	0.01 ± 0.02	7/7
	1973	17–20	18 ± 1.1	5/5	0.01–0.16	0.09 ± 0.10	2/2	0.08–0.14	0.11 ± 0.02	5/5
	1975	18–19	19 ± 0.7	2/3		Na		0.05–0.06	0.06 ± 0.01	2/3
Crab, king	1965	12	12	1/1		Na		Ns	Ns	1/1
Lithodes	1967	12–13	13 ± 0.9	2/37		Na		Ns	Ns	2/37
Lithodes	1971		Na			Na		Ns–2.4	0.43 ± 0.88	7/7
Ptarmigan	1970		11 ± 1.2	1/1		Na			0.25 ± 0.08	1/1
	1971	11–12	11 ± 0.6	3/3		Na		1.0–1.7	1.3 ± 0.4	3/3
	1972	11–13	12 ± 1.4	2/2		Na		0.72–0.73	0.73 ± 0.01	2/2
	1973	10–12	11 ± 0.8	5/5		Na		0.18–0.76	0.43 ± 0.25	5/5
	1974	10–13	11 ± 1.3	5/6		Na		0.39–1.1	0.80 ± 0.36	5/6
	1975	11–14	12 ± 1.5	3/8		Na		1.4–3.4	2.2 ± 1.1	3/8

*N, number of pooled samples/total number of organisms in all samples.

†Na, not analyzed; Ns, not significantly greater than background.

So that the variation with time of radionuclide concentration in the biological samples could be determined, the data for the results of analyses were segregated by year of collection and sample type for the natural and the long-lived fallout radionuclides in greatest concentration in the samples. The sample types selected were *Fucus distichus*, a brown alga from the marine environment; Dolly Varden, a char that lives in freshwater but often migrates to the sea and returns; and lichens, terrestrial cryptogamic plants. The radionuclides selected were ^{137}Cs , which has a half-life of 30 years, and ^{40}K . These data are given in Fig. 4 and indicate a decline with time for ^{137}Cs but not for ^{40}K . The decrease in the ^{137}Cs concentration suggests that the principal source of this radionuclide was fallout in the early 1960s, and the constant values for ^{40}K reflect a constant source of this radionuclide, as would be expected.

For the determination of the effect of area of collection, the best source of information appeared to be the data for ^{137}Cs in the freshwater moss

(*Fontinalis*) collected at six areas on Amchitka Island in the period from 1970 to 1975. These data are given in Fig. 5 and indicate that there are some, but not consistent, differences between areas. Therefore the area of collection has been removed as a variable in the interpretation of the data, and, generally, the results of analyses of collections from all areas of Amchitka have been transposed to a mean value for a single year.

Sample Types

Most of the remaining discussion of the interpretation of the radiometric data relates to sample type and radionuclide species. Since the two subjects are interrelated and cannot be clearly separated, they will be discussed separately at the expense of some redundancy.

Biological Samples. Indicator Species. About 90 sample types were analyzed, including whole samples for, or selected tissue samples from, 81 organisms; the remainder were soil, water, or air

samples. A review of the data for the 81 organisms indicated that little, if any, information would be lost by limiting the discussion to a few indicator species. An ideal indicator species is defined as a sessile species which significantly concentrates one or more radionuclides from the environment and which is readily available throughout the year to the collector in quantities sufficient to provide repeated samples of adequate size for analysis without a significant effect on the population of the organism in the collection area. On the basis of this definition, the following organisms have been selected as the principal indicator species for Amchitka Island:

Indicator species	Environment
<i>Fucus distichus</i> , a brown alga	Marine
<i>Fontinalis neomexicana</i> , a moss	Freshwater
<i>Ranunculus</i> sp., crowfoot	Freshwater
Lichens, cryptogamic plants	Terrestrial

The concentrations of fallout radionuclides by *Fucus* and by other marine algae were not greatly different, but *Fucus* was selected as the indicator species because of its accessibility and abundance at Amchitka and its use as an indicator species in Great Britain and other geographical areas. The sample collection areas for *Fucus* were Constantine Harbor, Duck Cove, Square Bay, and Sand Beach Cove. The most abundant fallout radionuclides in these samples were ^{95}Zr , ^{95}Nb , ^{137}Cs , and ^{144}Ce , and the greatest value for any of the four radionuclides was 1.5 pCi/g of dry weight (see Table A.1). The values for naturally occurring ^{40}K ranged from 23 to 46 pCi/g of dry weight for the same samples.

The radionuclides detected in the freshwater indicator species were the naturally occurring radionuclides ^7Be and ^{40}K and the fallout radionuclides ^{95}Zr , ^{95}Nb , ^{103}Ru , ^{106}Ru , ^{125}Sb , ^{137}Cs , ^{144}Ce , and ^{155}Eu (Tables A.2 and A.3). Of these radionuclides, ^7Be and ^{40}K were present in the greatest concentration (1 to 29 pCi/g of dry weight), whereas the concentrations of ^{95}Nb , ^{106}Ru , ^{137}Cs , and ^{144}Ce did not exceed 6.4 pCi/g of dry weight. Radionuclides commonly detected in aquatic vegetation samples collected prior to 1973 but only sporadically since 1973 include ^{54}Mn and ^{60}Co . The concentrations of radionuclides in *Fontinalis* and *Ranunculus* samples in 1974 were similar to those in aufwuchs and filamentous algae (Table A.4) and lichens (Table A.5) except that ^{155}Eu was not detected in the aufwuchs and greater concentrations of ^{137}Cs and ^{144}Ce were present in some 1974 aufwuchs and lichen samples than in the freshwater indicator species. Samples were collected from Clevenger

Creek, Bridge Creek, Duck Cove Creek, Mile Post 12 Creek, Ice Box Lake Inlet, and the outlets of Clevenger and Cannikin Lakes.

The indicator species selected for the terrestrial environment were lichens because of their well-established capability for accumulation of fallout radionuclides. The lichen samples were collected near Clam Lake, Ice Box Lake, and Cannikin Lake and were not sorted for species. *Cladonia rangifera* was the principal species reported by Koranda et al. (1969), but other species and mosses were also present in the samples used for analyses. A large array of fallout radionuclides, which included ^{95}Zr , ^{95}Nb , ^{103}Ru , ^{106}Ru , ^{125}Sb , ^{137}Cs , ^{144}Ce , and ^{155}Eu , was present in the lichen samples (see Table A.5). Of these, ^{137}Cs was the most abundant, and it was also more abundant than the naturally occurring radionuclides. The ranges of mean yearly values in terms of pCi/g of dry weight were 6 to 47 for ^{137}Cs , 5 to 15 for ^7Be (a naturally occurring radionuclide), and 1 to 6 for ^{40}K .

Food-Chain Organisms. Many species of fish, of commercial importance and otherwise, were collected and analyzed. The species that best represented the potential transfer of radionuclides from the sea to man were selected.

Of special interest are seafoods and other organisms that may be eaten by man. Although there are no significant commercial fisheries in the immediate vicinity of Amchitka (Merrell, Chap. 15, this volume), radionuclide data were obtained for salmon and Dolly Varden (Table A.6), halibut (Table A.7), and crab. The amount of ^{55}Fe and ^{137}Cs (the principal or only fallout nuclides present) and ^{40}K in muscle samples of these species by year for all collection sites is listed in Table 3. Similar information for the ptarmigan, a game bird present on Amchitka, is also given in Table 3 and supplemental information for the ptarmigan samples in Table A.8.

The predominant radionuclide was ^{40}K for all species for all years, with mean yearly values ranging from 11 to 20 pCi/g of dry weight. The values for ^{55}Fe and ^{137}Cs were severalfold less; this difference increased with time since the ^{40}K values remained relatively constant and the values for ^{55}Fe and ^{137}Cs declined. The decline was more rapid for ^{55}Fe than for ^{137}Cs . Another observation of interest was that landlocked Dolly Varden concentrated more ^{137}Cs , perhaps ten times more, than anadromous Dolly Varden captured after their return to freshwater. The maximum value for ^{137}Cs in muscle tissue of all the Dolly Varden samples was 8.2 pCi/g of dry weight for fish caught in a landlocked lake.

Many other species of fish were collected and analyzed (Tables A.9 and A.10), including greenling, which were sampled because they are an abundant inshore resident species. However, these data did not bring forth any new information. The wide array of marine invertebrates sampled, in addition to crabs, included sponges, snails, scallops, urchins, octopus, mussel, and plankton. Data for the sponge are given in Table A.11. The other species were not readily available in the intertidal zone, and most of the samples were obtained in 1971 and 1972 from otter-trawl catches by the *M. V. Commander*. Results of gamma-spectrum analyses of 40 samples are given in Table 7 of the 1973 Progress Report (Nelson and Seymour, 1974) and indicate no unusual kinds or amounts of radionuclides. The fallout radionuclides included ^{60}Co , ^{65}Zn , ^{95}Zr , ^{95}Nb , and ^{144}Ce . Their concentrations, with only a few exceptions, were less than 1 pCi/g of dry weight, whereas the ^{40}K values were usually greater by a factor of 10 or more.

Environmental Samples. The results of radio-metric analyses of air and water samples indicate the kinds and amounts of radionuclides that are potentially available for accumulation by plants and animals. Also, significant changes in the amounts or kinds of radionuclides in air samples can herald the arrival of new airborne radionuclides to an area.

Air. The air-sampling program was not continuous. Biweekly samples were collected from Oct. 2, 1970, to Nov. 12, 1971, weekly samples from Feb. 23, 1972, to Aug. 28, 1973, and a single 8-day sample in August–September 1974. This program was designed to detect fallout radionuclides in air particulates and did not include the use of a charcoal filter for the collection of radioactive gases.

Three air samplers, operated simultaneously, were used to collect air particulates; in August–September 1974, however, only one sampler was used. The airflow rate through a 15-cm filter head lined with Whatman No. 41 filter paper was about 500 m³/day. This paper has a retention index of 100 and retains particles of 5 μm and larger in diameter. The results of analyses are reported in Table A.12.

The most abundant radionuclides in the air samples were naturally occurring ^7Be and fallout radionuclides ^{95}Zr , ^{95}Nb , ^{103}Ru , ^{137}Cs , and ^{144}Ce . Because of their relatively short half-lives and large fission yield, a significant increase in the occurrence of ^{95}Zr , ^{95}Nb , and ^{103}Ru in the samples would indicate the arrival of fresh fallout. All the fallout radionuclide values for air samples were less than 10 fCi/m³ of air and often less than

1 fCi; however, the values for ^7Be ranged from 3 to 47 fCi/m³. A review of the radioactivity values for the short-lived fallout radionuclides indicates changes in values from time to time, but no strong correlation of radioactivity in Amchitka air samples with nuclear detonations at Lop Nor, China, was established.

The average yearly values for fallout radionuclides commonly detected in the samples (^{95}Zr , ^{95}Nb , ^{103}Ru , and ^{137}Cs) generally decreased during the period from 1970 to 1973. Niobium-95, for example, decreased from 5.9 to 0.04 fCi/m³ of air filtered. The average yearly value of naturally occurring ^7Be , however, remained between 16 and 20 fCi/m³ for the same period.

Air data obtained during 1974 from other sources (United States Environmental Protection Agency, 1973; 1974; LRE, Annual Report to Ebasco Services Inc., 1975, unpublished) indicated slightly greater amounts of radionuclides in airborne particulates and in precipitation in 1974 than 1973 from most stations in Alaska, Canada, and contiguous United States. This trend also would be expected at Amchitka, although the single 8-day sample taken in August–September 1974 did not contain detectable amounts of any radionuclide, including ^7Be . This may be explained by the relatively small volume of air sampled and the time of sampling, which was after the spring peak of stratospheric fallout.

Seawater. Both seawater and freshwater were sampled with a system of filters and sorption beds in a modified Battelle–Northwest Laboratories large-volume water sampler. The system consists of eight Millipore filters of 0.3- μm porosity which are 29 cm in diameter and which are arranged in parallel so that the water passes through the filters and then through one or more aluminum oxide beds arranged in series. An accurate analyses can be made of the filter papers for radionuclides 0.3 μm in diameter or larger retained on the filter paper, but the estimate of the fraction of the radionuclide in soluble form, as determined by analyses of the aluminum oxide beds, is less accurate because bed efficiency has not been precisely established for all radionuclides. The problem of determining bed efficiency is complicated by changes in the physical and chemical form of the nuclide which may occur naturally during efficiency calibration of the sampler. Also, ^3H and ^{40}K and perhaps some other radionuclides in ionic form are not captured by aluminum oxide. The results of seawater analyses for gamma-emitting radionuclides are reported in Table A.13.

Pre-Cannikin samples of offshore seawater were obtained in September 1970 and August 1971.

After the Cannikin detonation in November 1971, the collection of seawater samples was limited to intertidal areas. Cobalt-60, ^{65}Zn , and $^{110\text{m}}\text{Ag}$ were present in all seawater samples collected in September 1970; also present in some samples were ^{46}Sc , ^{54}Mn , and $^{108\text{m}}\text{Ag}$. The presence of $^{108\text{m}}\text{Ag}$ was unexpected, but it was identified qualitatively in the sample taken from the station farthest offshore on the Pacific Ocean side of Amchitka Island. The average concentrations of radionuclides in particulate form were 69, 120, and 44 pCi/m³ for ^{60}Co , ^{65}Zn , and $^{110\text{m}}\text{Ag}$, respectively; the fraction of each of these radionuclides in particulate form is about one-eighth for ^{60}Co and ^{65}Zn and two-thirds for $^{110\text{m}}\text{Ag}$. From these data the concentration of ^{60}Co , ^{65}Zn , and $^{110\text{m}}\text{Ag}$ in seawater was calculated to be 550, 1000, and 70 pCi/m³ of seawater, respectively. Fewer species of radionuclides were present in the seawater samples collected the following year, 1971.

Seawater samples collected after Cannikin were limited to the intertidal areas of Constantine Harbor, Duck Cove, and Sand Beach Cove, and the radionuclides detected were ^7Be , ^{95}Zr , ^{95}Nb , and ^{137}Cs . Beryllium-7 was present in the soluble fraction of the 1971–1972 samples from Constantine Harbor and Sand Beach Cove in amounts that averaged from 0.072 to 0.14 pCi/liter. Beryllium-7 was not detected in the soluble fraction of the 1971–1972 samples from Duck Cove but was slightly above the limit of detection in the particulate fraction. The fallout radionuclides were present in the 1971–1972 and 1974 particulate fraction and the 1971–1972 soluble fraction in amounts that averaged from nonsignificant to 0.046 pCi/liter. No radionuclides were detected in the six samples collected in 1973, but trace amounts of ^{95}Zr and ^{95}Nb were detected in the particulate fraction of some 1974 seawater samples. The significance of this observation is not obvious in light of the range of values for similar samples in other years, although both air and biological samples also indicated a slight increase in fallout radionuclides in 1974.

Freshwater. Samples for gamma-spectrum analyses were collected in August 1971, prior to Cannikin, and in each of the following years. The results of analyses of these samples are given in Table A.14.

Samples were obtained from Jones, Heart, DK-45, and Cannikin Lakes and Long Shot Mud Pit No. 1. The radionuclides detected included ^7Be , ^{95}Zr , ^{95}Nb , ^{137}Cs , and ^{144}Ce , but not all the radionuclides were present in all samples. For the lake samples, the values for ^7Be ranged from nondetectable to 4 pCi/liter, but for the fallout

radionuclides the annual values were less than 0.5 pCi/liter. The radionuclide values, except ^{137}Cs , for the Long Shot Mud Pit No. 1 samples were five times or more greater than comparable values for the lake-water samples. One possible explanation of this difference is that the mud-pit samples contained more particulate material than the lake-water samples. Like the seawater samples, the values for gamma-emitting radionuclides in freshwater declined to near zero in 1973 but increased slightly in 1974.

Both seawater and freshwater samples were also analyzed for tritium, and these analyses are discussed in the tritium section.

Soils and Sands

In 1975 surface soils and beach sands were added to the sample collection list. Samples of soils from the surface to a depth of 2.5 cm were collected from the main camp and in the vicinity of Cannikin surface ground zero. Beach sand samples of the same size were also collected at Constantine Harbor and Sand Beach Cove. The results of gamma-spectrum analyses are listed in Table A.15. The fallout radionuclides detected in the soil samples were ^{90}Sr , ^{95}Zr , ^{95}Nb , ^{106}Ru , ^{137}Cs , ^{141}Ce , and ^{144}Ce , but all the values for these radionuclides were less than 1 pCi/g of dry weight. The natural radionuclides ^{226}Ra , ^{228}Th , and ^{40}K were present in both soil and sand samples, and, in addition, trace quantities of ^{238}U were present in the beach sand samples. The amounts and species of fallout radionuclides in Amchitka soil samples were similar to those in soil samples collected in the western region of Washington State in 1973–1975 (Laboratory of Radiation Ecology, Annual Report to Ebasco Services, 1975, unpublished).

Background Radiation. The results of background-radiation measurements made in August 1974 and 1975 with a survey instrument are given in Table A.16. A survey meter with a thin end-window detector less than 2 mg/cm² was used without the beta shield. The detector was sensitive to beta-particle energies as low as 40 keV, and its efficiency for the detection of ^{60}Co gamma photons, measured in terms of dose rates, was about 5000 cpm/(mr/hr). Tritium cannot be detected by this survey meter since the maximum energy of the beta particles emitted by ^3H is 19 keV. The locations surveyed included the surface ground zero and adjacent areas for Long Shot, Milrow, and Cannikin. Maximum values recorded while holding the survey instrument 1 m above the ground ranged from 0.03 to 0.05 mr/hr. Average values at all sites were about 0.01 mr/hr or less.

These values are similar to those for values obtained from comparable surveys in other areas of the United States.

Radionuclide Species

Natural. The source of natural radionuclides in the environment of either terrestrial or atmospheric origin is constant, whereas the amounts and kinds of fallout radionuclides change with time and season in accordance with the input into the troposphere of fresh radionuclides from nuclear detonations and of older radionuclides from the stratosphere. Hence the amounts of natural radionuclides in one type of sample would be expected to be relatively constant from year to year, and a review of the radionuclide values in the appendix tables indicates that this is true. The variation for any one sample for any one year appears to be no greater than the sample variation between years. This also indicates year-to-year consistency in analytical procedures.

The natural gamma-emitting radionuclides in greatest concentrations were ^7Be and ^{40}K , but lesser concentrations of ^{226}Ra , ^{228}Th , and ^{238}U were detected in some samples. If the samples had been analyzed for alpha-emitting radionuclides, other natural radionuclides, such as radium and radon, would have been expected in amounts at or near the limit of detection.

In the samples the natural radionuclides were more abundant than the fallout radionuclides, usually by a factor of 10 or greater, and ^{40}K was more abundant than ^7Be except in lichen, aufwuchs, and water samples. Both lichens and aufwuchs have a great capacity to accumulate radionuclides by adsorption, and this may explain the greater values for ^7Be than for ^{40}K in these samples. For the water samples, the amount of ^{40}K was greatly underestimated. Potassium-40, which is principally in solution in seawater, is very poorly removed by the aluminum oxide beds of our water sampler; hence little or no ^{40}K was reported to be present in our samples, although the actual amount, which can be accurately calculated from the salinity, was about 300 pCi/liter.

Fallout

Gamma-Emitting Radionuclides. The gamma-emitting radionuclides detected most commonly by gamma-spectrum analyses were ^{95}Zr , ^{95}Nb , ^{137}Cs , and ^{144}Ce . Radionuclides detected less frequently include ^{46}Sc , ^{54}Mn , ^{60}Co , ^{65}Zn , ^{103}Ru , ^{106}Ru , $^{108\text{m}}\text{Ag}$, ^{125}Sb , and ^{155}Eu .

Four other radionuclides, ^3H , ^{55}Fe , ^{90}Sr , and $^{239,240}\text{Pu}$, have been given special attention, each for a different reason. Tritium is an excellent "tag"

for water and should be an excellent indicator of any movement of water away from the underground sites of the nuclear detonations. Iron-55 was found in relatively large quantities after the atmospheric detonations in the mid-Pacific and U.S.S.R. in 1961 and 1962, and, although its half-life is only 2.5 years, this radionuclide was the most abundant fallout radionuclide in the fishes of the world's oceans for many years after 1962. Strontium-90 has always been a fallout radionuclide of interest because it is chemically similar to calcium, is a relatively abundant fission product, and has a long half-life (28 years).

Tritium. The analysis of seawater and freshwater for tritium was a two-step process: (1) The purification of the sample by either a vacuum or an azotropic distillation process and (2) the measurement of ^3H in the distillate with a liquid scintillation system (Held et al., 1973). The analyses of biological samples for ^3H in tissue-water hydrogen (TWH) and tissue-bound hydrogen (TBH) were similar except that the first step for the analysis of TBH was preceded by a water-extraction procedure (Nelson and Seymour, 1975) that has recently been modified (Nelson and Seymour, 1976).

Tritium is produced naturally and by nuclear detonations. Natural tritium production by cosmic-ray interactions with atmospheric gases results in a ^3H concentration of a few tens of tritium units (TU)* in rainwater (Grosse et al., 1951; Perkins and Nielsen, 1965). After the advent of the nuclear age, the ^3H content of precipitation increased to a maximum of several thousand TU in 1963 owing to the release of tritium from nuclear explosions and, to a very small extent, from reactors and fuel-processing plants (Castagnola, 1969a). At Adak Island, which is only 300 km east of Amchitka, the monthly values in 1963 ranged from 550 to 3900 TU and the mean value was 1860 TU (International Atomic Energy Agency, 1971). Since the peak values in 1963, tritium levels in precipitation have decreased to present values of less than 100 TU.

The results of analyses of seawater and freshwater samples for ^3H by Teledyne Isotopes, the U. S. Geological Survey, and the Laboratory of Radiation Ecology for the years 1965 to 1975 are shown in Fig. 7 as mean yearly concentrations. Also in Fig. 7 are values for a special freshwater area, Long Shot Mud Pit No. 1. The results of ^3H analyses for single samples of seawater and freshwater for the period 1970 to 1975 are given in Table A.17.

*A tritium unit (TU) is one tritium atom per 10^{18} hydrogen atoms, or 3.23 pCi of ^3H per liter of water.

The seawater values for ^3H were less than the freshwater values, presumably because of the greater dilution in the ocean than in the small lakes of Amchitka Island of the ^3H that comes to the earth's surface in precipitation. The monthly mean value for ^3H in Amchitka seawater reached a maximum of 138 TU in 1967 (Essington, Forslow, and Castagnola, 1970) and has decreased since that time to 15 TU in 1975 (Table A.17). The latter number compares favorably with a predicted value of 15 to 30 TU that can be obtained by extrapolation of the data of Dockins et al. (1967) and by recognizing that only a few atmospheric detonations of nuclear devices have occurred since 1962.

The ^3H values for freshwater ponds, lakes, and streams shown in Fig. 7 are based on the results of analyses of 268 samples. [Excluded from the calculation of the yearly mean values were several hundred samples collected and analyzed by the U. S. Geological Survey for which the results of analyses were reported as less than 200 TU (pre-1973) or 150 TU (1973).] The maximum annual value recorded was 175 TU in 1966, the first year freshwater samples were collected. The yearly mean values steadily declined from 1966 to a value of 32 TU in 1974 and 34 TU in 1975. The amount of ^3H to be expected in freshwater at Amchitka can be estimated from the long-time continuous records of the amount of ^3H in precipitation at Valentia, a marine station in Ireland that is approximately the same latitude as Amchitka (Schell et al., 1974). Comparison of the Valentia and Amchitka data indicates that the amount of ^3H in surface waters at Amchitka and in rainfall at Valentia is of the same order of magnitude and is decreasing in a similar manner at the two stations. From this and the known values for ^3H in rainfall at Adak, Schell (personal communication, 1975) predicts that the amount of ^3H in Amchitka surface water now ranges from about 15 TU in winter to 140 TU in early summer.

The data for ^3H in water from the Long Shot ponds were not included with the data for the other freshwater samples since it was established soon after the Long Shot detonation that the radionuclide values for some water samples from this area were significantly greater than those from samples from other sites on Amchitka Island. Some tritium moved away from the underground site of the detonation, and the main front of activity reached the surface in September 1966, about 11 months after Long Shot. Tritium values in surface waters at that time reached a peak of 5130 TU in the drainage ditch 60 m east of surface ground zero (Castagnola, 1969b). In addition to ^3H , traces of radioiodine were also detected in 4 of 78 water samples during the initial breakthrough

of activity, and ^{85}Kr was found in soil gas stripped from water draining the Long Shot pad area (Castagnola, 1969b). Tritium, ^{85}Kr , and ^{131}I could be detected only in the samples from the immediate area surrounding Long Shot surface ground zero, and only tritium was detectable one year after Long Shot.

So that the amount of ^3H in groundwater could be further investigated, shallow wells were dug in the Long Shot area in late 1971. Analyses of water from these wells indicated that the maximum ^3H concentrations were in samples from a depth between 200 and 300 ft (60 and 90 m) below the surface and that the concentration of ^3H decreased at greater depths. Tritium also decreased with distance away from the Long Shot placement hole. Thus "these observations indicate that gaseous activity, mostly tritium and krypton, moved at an early time to the top of the chimney (which at Long Shot did not reach the surface). As the chimney filled with water, these gases were pushed ahead upwards, passing through uncompacted material in the upper portion of the stemming, out into the spall zone, where they went into solution" (Merritt, 1973).

Figure 7 indicates that the mean yearly values for Long Shot Mud Pit No. 1 approached a maximum of 1800 TU in 1966 and 1967, decreased to 850 TU in 1968, increased again to 1750 TU in 1971, and declined to 900 TU in 1975. Because heavy rainfall is believed to have significantly diluted the sample collected in 1975, the value for the sample collected 3 m downstream from Long Shot Mud Pit No. 1 was used (Nelson and Seymour, 1976). Although some single sample values for Long Shot Mud Pit No. 1 exceeded 5000 TU, all the values are well below the Maximum Permissible Concentration for ^3H in water (MPC_w) for occupational exposure. This value is $3 \times 10^{-2} \mu\text{Ci}$ of ^3H per milliliter of water, equivalent to 9×10^6 TU, and was established by the International Commission on Radiological Protection (ICRP) (1959) and the U. S. National Committee on Radiation Protection (NCRP) (1959). For an individual member of the population in an uncontrolled area, the Radiation Protection Guide (RPG) value is one-tenth the MPC for occupational exposure, or $3 \times 10^{-3} \mu\text{Ci}$ of ^3H per milliliter of water, which is equivalent to 9×10^5 TU (Energy Research and Development Administration, 1975a). The average value for the general population is less than that for the individual, and, for isotopes that concentrate in organs other than the gonads, a value of one-thirtieth the MPC value for continuous occupational exposure, or $10^{-3} \mu\text{Ci}$ of ^3H (3×10^5 TU), has been established by the International Commission on Radiological Protec-

tion (1964). Another perspective on the significance of ^3H in the Amchitka samples is obtained by a comparison of the maximum values of 5000+ TU at Amchitka (Long Shot Mud Pit No. 1) with values for ^3H in rainfall at other areas. At nearby Adak in the Aleutian Islands, where the concentration of ^3H in precipitation can be assumed to be about the same as that at Amchitka, monthly samples have been collected, and in 1963 the mean value was 1860 TU and the maximum 3900 TU (International Atomic Energy Agency, 1971). Although the tritium concentration in Long Shot Mud Pit No. 1 at Amchitka was somewhat greater than in precipitation at Adak in 1963, it was comparable to the tritium concentration in precipitation in the Central United States (Stewart and Farnsworth, 1968), a continental location where the concentration of ^3H in precipitation is expected to be significantly greater than at a coastal location, such as Adak or Amchitka. Also, in 1963 the tritium concentration in precipitation at another continental site, Vienna, Austria, ranged from 800 TU to almost 6000 TU (Schell et al., 1974).

No tritiated water has been observed in the samples collected for the Milrow or Cannikin events, probably because the rubble chimneys reached the surface, and, if the tritium or krypton came to the surface with the rising water in the chimney, it dissipated at undetectable levels. Also, the emplacement holes contained plugs of epoxy cement, which prevented the stemming from being an escape route (Merritt, 1973).

In addition to the measurement of the ^3H concentrations in seawater and freshwater, measurements of ^3H in seafoods from two sources were also made. Samples of canned salmon, crab, scallops, and shrimp caught in Alaska and Washington waters before and after Cannikin were provided by the National Cannery Association for analysis by the Environmental Protection Agency's National Environmental Research Center in Las Vegas, Nev. A second set of samples was collected near Amchitka by the Fisheries Research Institute, University of Washington, and also forwarded to the EPA laboratory for analysis. These samples included salmon caught before Cannikin and salmon, halibut, cod, and crab caught after Cannikin.

The results of analyses for total tritium, i.e., tritium in tissue-water hydrogen (TWH) plus tissue-bound hydrogen (TBH), are given in three EPA reports (Fort and Wruble, 1972; United States Environmental Protection Agency, 1972; United States Environmental Protection Agency, 1973). The values were less than the limit of detection, 200 to 300 TU, for most samples, and the

maximum value was 540 ± 240 TU. For all samples, including those collected before and after Cannikin and from areas near and at a distance from Amchitka, the tritium values were essentially the same, and hence no relationship of Cannikin to the concentration of ^3H in seafoods was observed.

Another set of samples was collected in August 1975 and analyzed by the Laboratory of Radiation Ecology for ^3H in TWH and in TBH. The species sampled were *Fucus*, greenling, Dolly Varden, and *Fontinalis*, and the results of the analyses are given in Table A.18. The ^3H values for TWH and for ambient water (Table A.17) were essentially the same for organisms from freshwater, saltwater, and the Long Shot Mud Pit drainage area. Hence there appears to be a free exchange of ambient and tissue water without any apparent change in ^3H concentration. Others (Bruner, 1973; Robertson, 1973; and Feinendegen, 1967) have made similar observations and have also reported that the half-life for TWH for a variety of animal species ranges from 1 to 20 days.

Although the ^3H concentrations in ambient water and TWH were the same, ^3H concentration in TBH was two to five times greater than that in TWH for the same sample. The greater ^3H values for TBH are not unexpected if the turnover rate for ^3H in TBH is relatively long and if the ^3H concentration in ambient water was greater in the spring of 1975 than in August 1975; both of these suppositions are believed to be true for the following reasons. Whereas the half-life for TWH, as noted above, is 1 to 20 days, the half-life for TBH has been reported to range from 110 to 300 days for animals (Robertson, 1973; Harrison, Koranda, and Tucker, 1973) and up to 2.7 years for plants (Stewart, Rosenthal, and Kline, 1973). In regard to the spring and summer 1975 values for ^3H in ambient water, Schell et al. (1974) have shown that the ^3H content of rainfall consistently varies within a single year by a factor of 5 or more with the maximum value occurring in the spring and the minimum value in the winter. Also, ^3H values for freshwater samples collected at Amchitka in May 1974 were found to be twice as great as those for similar samples collected 3 months later (August 1974). Therefore the comparison of ^3H values in TWH and TBH for samples collected in August 1975 is essentially a comparison of ^3H in ambient water of August 1975 (TWH) and spring 1975 (TBH); greater values for ^3H in TBH were expected.

Iron-55. This radionuclide is produced in nuclear detonations by neutron activation and was relatively abundant in the fishes of the world's oceans after the 1961–1962 series of atmospheric

nuclear detonations. So that the current background values for ^{55}Fe in seafoods could be established, samples of canned salmon and of fresh fish were analyzed for ^{55}Fe as a part of the Amchitka program. The results of analyses for canned salmon for the years 1971 and 1972 are reported by Nelson and Seymour (1974), and the results for fresh fish are given in Tables 3 and A.10.

The canned salmon sampled included sockeye, Chinook, and chum species obtained by EPA's Environmental Research Center, Las Vegas, from five canneries in Bristol Bay, Alaska. Values for single samples ranged from 0.45 to 3.68 pCi of ^{55}Fe per gram of dry weight. These values are ascribed, totally, to worldwide fallout, probably of 1961–1962 origin.

The species of fresh fish sampled at Amchitka from 1969 to 1974 for ^{55}Fe analysis included pink salmon, Dolly Varden, halibut, and greenling. The amount of ^{55}Fe in muscle samples for all species ranged from 0.05 to 6.7 pCi/g of dry sample. Values for liver and viscera samples were greater than those for muscle, and the maximum value was 57 pCi of ^{55}Fe per gram of dry weight in a liver sample. In 1969 the amount of naturally occurring ^{40}K in the muscle samples was several times greater than the amount of ^{55}Fe , and this difference has steadily increased in recent years as the amount of ^{55}Fe in marine fish has continued to decline.

Strontium-90. Only a few samples (plants, grasses, the exoskeleton of crabs, and the bones of rats, ptarmigan, fish, and seals) have been analyzed for ^{90}Sr . Results of analyses of ^{90}Sr in rat and ptarmigan bone are reported in Table A.19. Results of the analyses of the other samples are reported in Seymour and Nakatani (1967) and in Isakson and Seymour (1968).

The sample with the greatest ^{90}Sr content was the bone of a Dolly Varden collected in 1965; the value was 71 pCi/g of dry weight. Values for ptarmigan (1971 to 1975) ranged from 11 to 35 pCi/g of dry weight and for rats (1965 to 1975) 0.5 to 10 pCi/g of dry weight. The values for seal bone, greenling bone, and king crab exoskeleton were near or below the limits of detection. The amount of ^{90}Sr in plants and grasses (crowberry, wild rye, grass, and moss) collected only in 1965 ranged from 1 (wild rye) to 15 (moss) pCi/g of dry weight. The data for ptarmigan indicate a decrease in ^{90}Sr concentration from 1971 to 1974, but there was no significant change in the values for the rat samples (Table A.19); however, the small number of samples analyzed precludes any definitive statement about the significance of any observed changes in ^{90}Sr concentration. The concen-

tration of ^{90}Sr in plants and animals would be expected to be slowly decreasing since the peak of ^{90}Sr fallout at Adak, 300 km from Amchitka, was reported to have occurred in 1963 (Energy Research and Development Administration, 1975b).

Plutonium-239, 240. In 1975 selected samples (soil, sand, *Fucus*, and greenlings) were also analyzed for $^{239,240}\text{Pu}$; results of the analyses are listed in Table A.20. In terms of dry sample weight, the values ranged from 0.015 to <0.002 pCi/g. The values for Amchitka soils were similar to values for September 1974 soil samples from the western region of Washington State, 0.005 to 0.012 pCi of $^{239,240}\text{Pu}$ per gram of dry weight (Laboratory of Radiation Ecology, Annual Report to Ebasco Services, Inc., 1975, unpublished). The values for brown alga, *Fucus distichus*, from Amchitka were somewhat less than $^{239,240}\text{Pu}$ values for the alga, *Sargassum* sp., collected in 1970 from the Atlantic Ocean but somewhat greater than values for *Fucus vesiculosa* collected at Woods Hole in 1971 (Noshkin et al., 1973) and for *Pelagophycus porra* collected from the California Coast in 1971 (Wong, Hodge, and Folsom, 1972). From this evidence the source of $^{239,240}\text{Pu}$ for the samples from Amchitka and other areas is assumed to be the same, worldwide fallout.

CONCLUSION

There has been essentially no escape of radionuclides from the sites of the Long Shot, Milrow, and Cannikin underground nuclear detonations. Radionuclide values for Amchitka samples were similar to those for comparable samples from other geographical areas. The only radioactivity of Amchitka nuclear test origin that was detected consisted of trace quantities of radionuclides, principally tritium, in water and soil gas samples in the immediate vicinity of surface ground zero for the Long Shot detonation.

The naturally occurring radionuclides ^{40}K and ^7Be were the most abundant radionuclides in the samples except for ^{137}Cs in lichen samples. Potassium-40 was the most abundant natural radionuclide except for water samples, air particulates, and freshwater moss, aufwuchs, and filamentous algae, where ^7Be was the predominant radionuclide. (The system used for the collection of water samples did not effectively retain ^{40}K in ionic form.) The principal fallout radionuclides present were ^{95}Zr , ^{95}Nb , ^{137}Cs , and ^{144}Ce . The indicator species used for fallout radionuclides at Amchitka Island were lichens for the terrestrial environment, *Ranunculus* sp., *Fontinalis* sp., or aufwuchs for the

freshwater environment, and *Fucus distichus* for the marine environment. Plankton was not collected regularly but would be expected to be another good indicator of fallout radionuclides. The most likely pathway to man for radionuclides produced at Amchitka would be via seafoods (halibut, salmon, and king crab), although there is virtually no commercial fishery in the immediate vicinity of Amchitka Island. Values for the fallout radionuclides were often near or below the limits of detection with attendant large error terms.

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APPENDIX

AMCHITKA RADIOBIOLOGICAL DATA (NELSON AND SEYMOUR, 1975;1976)

Table A.1—Gamma-Emitting Radionuclides in the Marine Alga *Fucus* Collected at Amchitka Island

Location and date	No.	Gamma-emitting radionuclides,* pCi/g of dry weight					
		⁷ Be	⁴⁰ K	⁹⁵ Zr	⁹⁵ Nb	¹³⁷ Cs	¹⁴⁴ Ce
Composite from several sites							
1965†	1	Na	34‡	Ns	Ns	0.10‡	Ns
Cyril Cove							
1967†	2	Na	24 ± 0.3	Na	Na	0.06 ± 0.01	Ns
Makarius Bay							
1967†	2	Na	25 ± 1.8	Ns	Ns	0.06 ± 0.0	Ns
1968†	2	Na	46 ± 2.8	Na	Na	Ns	0.64 ± 0.42
Constantine Harbor							
1970–1971†	3	0.52 ± 0.18	25 ± 6	0.10 ± 0.08	0.21 ± 0.17	0.05 ± 0.02	Na
1972	4	2.5 ± 2.0	34 ± 2	0.04 ± 0.04	0.07 ± 0.08	Ns	Ns
1973	2		34 ± 0.7	Ns	Ns	0.03 ± 0.04	Ns
May 1974	1	1.0 ± 0.4	32 ± 2.0	0.36 ± 0.04	0.73 ± 0.09	0.05 ± 0.03	1.5 ± 0.2
August 1975	1	1.7 ± 1.3	32 ± 2.3	Ns	Ns	0.04 ± 0.04	Ns
Duck Cove							
1970–1971†	3	0.8 ± 0.3	23 ± 2	0.07 ± 0.04	0.15 ± 0.10	0.04 ± 0.02	Na
1971–1972	5	1.9 ± 1.5	35 ± 4.5	0.05 ± 0.03	0.10 ± 0.07	0.01 ± 0.03	
1973	3	0.47 ± 0.41	35 ± 9.9	Ns	Ns	0.03 ± 0.05	0.08 ± 0.14
May 1974	1	Ns	38 ± 1.2	0.08 ± 0.06	0.22 ± 0.05	0.07 ± 0.02	0.91 ± 0.10
August 1974	1	Ns	36 ± 2.3	Ns	Ns	0.07 ± 0.04	0.35 ± 0.21
August 1975	1	Ns	33 ± 2.3	Ns	Ns	Ns	Ns
Square Bay							
August 1975	1	Ns	38 ± 2.4	Ns	Ns	Ns	Ns
Sand Beach Cove							
1970–1971†	5	0.09 ± 0.09	26 ± 6	0.08 ± 0.06	0.17 ± 0.14	0.06 ± 0.03	Na
1971–1972	6	3.8 ± 3.2	26 ± 4.6	0.22 ± 0.20	0.45 ± 0.43	0.01 ± 0.02	Ns
1973	2	Ns	35 ± 2.1	Ns	Ns	Ns	0.16 ± 0.23
May 1974	1	0.61 ± 0.45	39 ± 2.3	0.23 ± 0.09	0.34 ± 0.08	Ns	0.92 ± 0.19
August 1974	1	Ns	27 ± 1.4	Ns	Ns	Ns	0.25 ± 0.19
August 1975	1	Ns	34 ± 2.2	Ns	0.16 ± 0.12	0.04 ± 0.04	Ns

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

†Pre-Cannikin.

‡Counting errors were not given in the original reference (Seymour and Nakatani, 1967).

Table A.2—Gamma-Emitting Radionuclides in the Freshwater Moss *Fontinalis neomexicana* Collected at Amchitka Island

Location and date	No.	Gamma-emitting radionuclides,* pCi/g of dry weight									
		⁷ Be	⁴⁰ K	⁹⁵ Zr	⁹⁵ Nb	¹⁰³ Ru	¹⁰⁶ Ru	¹²⁵ Sb	¹³⁷ Cs	¹⁴⁴ Ce	¹⁵⁵ Eu
Clevenger Creek											
1970–1971†	4	8 ± 4	5.8 ± 3.0	1.4 ± 1.0	2.9 ± 2.3	0.28 ± 0.54	3.2 ± 1.2	1.4 ± 0.6	4.0 ± 1.5	Na	Na
1971–1972	5	2.7 ± 4.3	6.2 ± 2.1	0.6 ± 0.3	2.0 ± 2.0	0.67 ± 0.87	0.54 ± 0.75	0.18 ± 0.4	1.9 ± 1.2	1.1 ± 1.6	Ns
1973	2	4.5 ± 1.1	5.4 ± 0.2	Ns	0.15 ± 0.21	0.07 ± 0.10	0.74 ± 0.18	0.23 ± 0.03	2.3 ± 1.1	0.84 ± 0.37	0.22 ± 0.01
May 1974	1	17 ± 11	3.9 ± 1.8	2.4 ± 1.2	3.4 ± 0.8	Ns	3.1 ± 0.9	0.55 ± 0.16	1.2 ± 0.1	2.8 ± 0.3	0.26 ± 0.10
August 1974	1	4.3 ± 1.9	5.7 ± 1.4	0.7 ± 0.3	1.5 ± 0.2	Ns	2.5 ± 0.5	0.31 ± 0.10	1.5 ± 0.1	3.9 ± 0.3	0.27 ± 0.06
August 1975	1	4.2 ± 2.0	6.3 ± 1.4	Ns	0.44 ± 0.18	Ns	0.88 ± 0.47	0.17 ± 0.09	0.7 ± 0.1	2.3 ± 0.3	0.08 ± 0.06
Bridge Creek											
1970–1971†	3	10 ± 5	7.3 ± 3.2	1.7 ± 1.4	3.9 ± 3.1	Ns	4.4 ± 2.5	1.2 ± 0.8	4.1 ± 3.0	Na	Na
1971–1972	5	6.2 ± 2.8	6.8 ± 1.0	1.0 ± 0.6	2.2 ± 1.5	0.6 ± 0.8	1.1 ± 1.3	0.4 ± 0.6	3.3 ± 1.3	0.52 ± 1.2	Ns
1973	2	5.1 ± 1.4	5.8 ± 0.4	Ns	0.08 ± 0.11	Ns	Ns	0.14 ± 0.19	2.3 ± 1.9	1.1 ± 0.5	0.11 ± 0.15
May 1974	1	5.2 ± 0.9	7.9 ± 1.6	2.1 ± 0.2	4.4 ± 0.2	0.24 ± 0.10	3.5 ± 0.6	0.33 ± 0.11	1.9 ± 0.1	4.5 ± 0.3	0.18 ± 0.06
August 1974	1	3.6 ± 2.5	5.2 ± 1.8	1.0 ± 0.3	2.1 ± 0.3	Ns	2.3 ± 0.7	0.20 ± 0.15	1.0 ± 0.1	4.6 ± 0.4	0.23 ± 0.09
August 1975	1	3.3 ± 2.2	5.8 ± 1.7	0.3 ± 0.3	0.6 ± 0.23	Ns	1.7 ± 0.7	0.25 ± 0.14	1.1 ± 0.1	3.1 ± 0.4	0.10 ± 0.08
Duck Cove Creek											
1970–1971†	3	8 ± 3	6.6 ± 2.6	1.3 ± 1.1	2.7 ± 2.3	0.5 ± 0.6	2.8 ± 1.5	1.4 ± 0.5	2.6 ± 1.1	Na	Na
1971–1972	5	6.4 ± 5.4	6.1 ± 0.8	0.5 ± 0.2	1.3 ± 0.8	0.9 ± 1.2	1.2 ± 1.0	1.1 ± 0.5	1.7 ± 0.9	0.32 ± 0.72	Ns
1973	2	7.1 ± 7.0	6.4 ± 0.4	Ns	Ns	Ns	0.65 ± 0.92	0.32 ± 0.23	1.2 ± 0.5	0.9 ± 1.3	0.09 ± 0.13
May 1974	1	7.4 ± 1.0	5.4 ± 1.2	1.6 ± 0.2	3.5 ± 0.2	0.36 ± 0.11	3.4 ± 0.6	0.53 ± 0.13	2.2 ± 0.1	5.7 ± 0.3	1.16 ± 0.05
August 1974	1	1.4 ± 0.8	<6	Ns	0.21 ± 0.08	Ns	0.29 ± 0.19	Ns	0.8 ± 0.1	0.34 ± 0.1	Ns
August 1975	1	1.9 ± 1.2	5.4 ± 1.1	0.2 ± 0.2	0.65 ± 0.15	Ns	0.69 ± 0.44	0.26 ± 0.09	0.8 ± 0.1	2.4 ± 0.26	0.09 ± 0.05
Long Shot drainage											
August 1975	1	4.4 ± 1.2	4.0 ± 1.3	0.2 ± 0.1	0.61 ± 0.13	Ns	2.3 ± 0.4	0.27 ± 0.01	1.2 ± 0.1	3.2 ± 0.2	0.2 ± 0.08
Mile Post 12 Creek											
1973	2	9.0 ± 8.6	4.7 ± 2.0	Ns	0.17 ± 0.23	Ns	0.7 ± 0.9	0.12 ± 0.17	2.0 ± 1.2	1.4 ± 0.8	0.09 ± 0.12
May 1974	1	13 ± 1.0	6.0 ± 1.1	1.4 ± 0.13	3.4 ± 0.18	0.20 ± 0.05	4.1 ± 0.6	0.23 ± 0.10	2.1 ± 0.1	6.0 ± 0.3	0.16 ± 0.04
August 1974	1	4.5 ± 2.0	5.8 ± 1.2	0.8 ± 0.3	1.3 ± 0.3	Ns	1.9 ± 0.6	Ns	0.7 ± 0.1	3.9 ± 0.3	0.13 ± 0.06
August 1975	1	6.5 ± 1.8	4.5 ± 1.7	0.3 ± 0.2	0.67 ± 0.18	Ns	2.7 ± 0.7	Ns	0.5 ± 0.1	5.2 ± 0.3	0.21 ± 0.11
Ice Box Lake inlet											
1973	2	4.1 ± 0.8	5.7 ± 1.0	Ns	0.08 ± 0.11	Ns	0.5 ± 0.0	0.28 ± 0.06	1.5 ± 0.6	0.87 ± 0.12	0.17 ± 0.08
May 1974	1	3.7 ± 0.6	5.0 ± 1.0	0.70 ± 0.09	1.2 ± 0.11	Ns	1.0 ± 0.4	0.20 ± 0.09	3.1 ± 0.1	2.4 ± 0.21	0.13 ± 0.04
August 1974	1	2.3 ± 0.8	5.9 ± 0.5	0.17 ± 0.14	0.6 ± 0.1	Ns	0.9 ± 0.3	0.23 ± 0.08	1.0 ± 0.1	1.6 ± 0.2	Ns
August 1975	1	Ns	4.7 ± 1.3	Ns	0.27 ± 0.16	Ns	0.7 ± 0.5	0.20 ± 0.11	1.3 ± 0.1	1.8 ± 0.3	0.09 ± 0.07
Cannikin Lake outlet											
1973	2	7.3 ± 0.5	6.2 ± 0.7	0.09 ± 0.12	0.16 ± 0.23	0.07 ± 0.09	0.6 ± 0.8	0.30 ± 0.18	3.9 ± 4.6	1.1 ± 0.4	0.15 ± 0.21
May 1974	1	10 ± 1.0	2.4 ± 0.6	1.2 ± 0.12	2.7 ± 0.15	0.24 ± 0.13	2.2 ± 0.3	0.29 ± 0.05	1.1 ± 0.1	6.3 ± 0.2	0.13 ± 0.03
August 1974	1	Ns	4.2 ± 0.6	1.2 ± 0.15	2.3 ± 0.17	0.21 ± 0.11	2.6 ± 0.5	0.33 ± 0.12	1.6 ± 0.1	6.4 ± 0.3	Ns
August 1975	1	7.9 ± 1.9	5.1 ± 1.1	Ns	0.52 ± 0.16	Ns	1.8 ± 0.5	0.24 ± 0.09	2.0 ± 0.1	2.1 ± 0.3	Ns

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

†Pre-Cannikin.

Table A.3—Gamma-Emitting Radionuclides in the Freshwater Plant *Ranunculus* sp. Collected at Amchitka Island

Location and date	No.	Gamma-emitting radionuclides,* pCi/g of dry weight									
		⁷ Be	⁴⁰ K	⁹⁵ Zr	⁹⁵ Nb	¹⁰³ Ru	¹⁰⁶ Ru	¹²⁵ Sb	¹³⁷ Cs	¹⁴⁴ Ce	¹⁵⁵ Eu
Clevenger Creek											
1970–1971†	4	4.1 ± 4.7	21 ± 4	0.6 ± 0.8	1.3 ± 1.6	Ns	1.9 ± 1.8	0.3 ± 0.6	1.7 ± 1.1	Na	Na
1971–1972	5	5.0 ± 8.7	16 ± 1.6	0.36 ± 0.49	0.99 ± 0.96	0.54 ± 0.53	0.6 ± 0.8	0.5 ± 0.54	1.6 ± 0.7	Na	Na
1973	2	1.9 ± 2.7	22 ± 3.5	Ns	Ns	Ns	Ns	Ns	0.8 ± 0.5	0.3 ± 0.4	Ns
May 1974	1	3.1 ± 0.6	24 ± 1.6	0.80 ± 0.10	1.8 ± 0.1	0.12 ± 0.08	1.0 ± 0.4	0.14 ± 0.09	0.87 ± 0.07	2.3 ± 0.2	Ns
August 1974	1	1.4 ± 1.4	15 ± 1.3	Ns	Ns	Ns	Ns	Ns	0.24 ± 0.07	0.5 ± 0.3	Ns
August 1975	1	Ns	19 ± 2.3	Ns	Ns	Ns	Ns	Ns	0.52 ± 0.09	0.34 ± 0.3	Ns
Bridge Creek											
1970–1971†	3	8.4 ± 5.8	17 ± 3	1.0 ± 0.4	2.3 ± 1.0	Ns	2.1 ± 0.5	0.5 ± 0.5	3.2 ± 0.2	Na	Na
1971–1972	5	3.6 ± 5.0	21 ± 7.6	0.36 ± 0.22	0.78 ± 0.48	0.19 ± 0.30	0.62 ± 0.91	0.3 ± 0.4	2.2 ± 1.4	Na	Na
1973	1	4.7 ± 1.5	29 ± 2.3	Ns	Ns	Ns	Ns	Ns	1.2 ± 0.1	0.7 ± 0.2	0.15 ± 0.10
May 1974	1	3.8 ± 0.8	19 ± 2.5	1.1 ± 0.2	2.4 ± 0.2	0.15 ± 0.09	1.5 ± 0.6	0.23 ± 0.12	1.6 ± 0.1	3.4 ± 0.3	Ns
August 1974	1	2.0 ± 0.8	19 ± 0.8	0.4 ± 0.1	0.7 ± 0.1	Ns	0.94 ± 0.32	0.16 ± 0.08	0.85 ± 0.06	1.7 ± 0.2	Ns
August 1975	1	2.5 ± 1.2	21 ± 2.2	Ns	0.35 ± 0.13	Ns	0.67 ± 0.46	Ns	1.2 ± 0.1	1.0 ± 0.23	Ns
Duck Cove Creek											
1970–1971†	2	4.0 ± 3.5	15 ± 8	0.41 ± 0.15	0.86 ± 0.32	Ns	1.0 ± 1.0	0.7 ± 0.5	1.3 ± 0.4	Na	Na
1971–1972	5	6.2 ± 8.9	20 ± 5	0.42 ± 0.24	0.94 ± 0.57	0.52 ± 0.66	0.87 ± 0.80	0.6 ± 0.4	1.6 ± 0.9	Na	Na
1973	1	6.0 ± 1.5	20 ± 1.5	Ns	Ns	Ns	Ns	0.26 ± 0.09	2.9 ± 0.1	0.9 ± 0.2	0.14 ± 0.08
May 1974	1	3.1 ± 0.7	14 ± 1.5	0.46 ± 0.09	1.2 ± 0.1	0.16 ± 0.08	0.81 ± 0.36	Ns	4.0 ± 0.2	1.8 ± 0.2	Ns
August 1974	1	Ns	21 ± 2	Ns	0.47 ± 0.19	Ns	Ns	Ns	0.67 ± 0.08	0.78 ± 0.22	Ns
August 1975	1	Ns	13 ± 1.8	Ns	Ns	Ns	0.63 ± 0.43	Ns	1.6 ± 0.13	0.85 ± 0.24	Ns
Clevenger Creek outlet											
1970–1971†	2	2.5 ± 2.2	5.3 ± 3.5	0.39 ± 0.07	0.81 ± 0.16	0.4 ± 0.5	0.5 ± 0.6	0.6 ± 0.1	0.6 ± 0.8	Na	Na
1971–1972	5	12 ± 14	10 ± 9	0.78 ± 0.86	2.5 ± 2.4	0.9 ± 1.3	1.2 ± 0.4	0.1 ± 0.2	1.1 ± 0.1	Na	Na
1973	1	3.4 ± 1.0	20 ± 2.1	Ns	Ns	Ns	Ns	Ns	0.3 ± 0.1	Ns	Ns
August 1974	1	Ns	24 ± 1.1	0.45 ± 0.20	0.80 ± 0.19	Ns	Ns	Ns	0.7 ± 0.1	1.4 ± 0.3	Ns
August 1975	1	1.9 ± 0.7	18 ± 1.5	Ns	0.07 ± 0.07	Ns	0.5 ± 0.3	Ns	0.8 ± 0.1	0.6 ± 0.2	Ns
Long Shot drainage											
August 1975	1	5.3 ± 2.4	19 ± 3.0	Ns	0.42 ± 0.26	Ns	1.3 ± 0.8	Ns	1.0 ± 0.1	1.4 ± 0.4	Ns
Cannikin Lake outlet											
May 1974	1	13 ± 1.2	17 ± 1.8	1.6 ± 0.2	3.9 ± 0.2	0.45 ± 0.13	3.4 ± 0.6	Ns	1.3 ± 0.1	6.4 ± 0.3	0.20 ± 0.06
August 1974	1	3.5 ± 1.3	28 ± 3.3	0.31 ± 0.19	0.60 ± 0.16	Ns	1.2 ± 0.8	Ns	1.4 ± 0.1	2.0 ± 0.3	Ns
August 1975	1	2.3 ± 0.9	10 ± 1.5	Ns	0.18 ± 0.09	Ns	Ns	0.22 ± 0.1	2.9 ± 0.2	1.5 ± 0.2	0.14 ± 0.06

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean.
Na, not analyzed; Ns, not significant.

†Pre-Cannikin.

Table A.4—Gamma-Emitting Radionuclides in Freshwater Aufwuchs and Filamentous Algae Collected at Amchitka Island*

Location and date	No.	Gamma-emitting radionuclides,† pCi/g of dry weight								
		⁷ Be	⁴⁰ K	⁹⁵ Zr	⁹⁵ Nb	¹⁰³ Ru	¹⁰⁶ Ru	¹²⁵ Sb	¹³⁷ Cs	¹⁴⁴ Ce
Long Shot Pond										
1970–1971‡	7	15 ± 12	9 ± 4	3.1 ± 1.9	6.7 ± 3.9	2.1 ± 2.7	5.8 ± 4.1	1.5 ± 0.9	1.8 ± 0.9	Na
1971–1972	5	3.2 ± 3.4	10 ± 1.4	0.8 ± 1.0	2.2 ± 2.9	0.39 ± 0.56	0.2 ± 0.4	0.4 ± 0.3	0.5 ± 0.1	1.1 ± 1.6
1973	2	3.7 ± 2.1	9.8 ± 0.4	Ns	0.09 ± 0.12	Ns	Ns	Ns	0.27 ± 0.02	0.42 ± 0.26
May 1974	1	26 ± 9	4.9 ± 1.4	Ns	4.6 ± 1.0	Ns	2.5 ± 0.8	0.39 ± 0.13	0.40 ± 0.07	7.7 ± 0.6
August 1974	1	3.4 ± 1.0	9.4 ± 0.8	0.55 ± 0.15	0.92 ± 0.14	Ns	1.3 ± 0.4	0.24 ± 0.09	0.34 ± 0.05	1.2 ± 0.2
August 1975	1	2.8 ± 1.8	9.8 ± 1.6	Ns	0.28 ± 0.19	Ns	Ns	0.21 ± 0.09	0.19 ± 0.05	1.4 ± 0.3
Mile Post 12 Creek										
July 1972	1	7.8 ± 1.7	5.2 ± 0.5	3.5 ± 0.4	6.4 ± 0.5	1.7 ± 0.3	0.76 ± 0.28	Ns	2.0 ± 0.2	3.8 ± 0.4
August 1973	1	8.3 ± 0.9	9.6 ± 1.6	0.29 ± 0.11	0.34 ± 0.08	0.24 ± 0.09	Ns	Ns	2.7 ± 0.1	0.36 ± 0.17
May 1974	1	9.1 ± 1.1	8.9 ± 1.6	4.0 ± 0.2	7.6 ± 0.3	0.28 ± 0.13	2.9 ± 0.7	0.79 ± 0.13	2.5 ± 0.2	12 ± 0.5
August 1975	1	13 ± 1.2	6.2 ± 1.5	0.36 ± 0.11	0.97 ± 0.12	Ns	2.3 ± 0.5	0.26 ± 0.10	2.3 ± 0.1	3.2 ± 0.2
White Alice Inlet to Cannikin Lake										
August 1973	1	23 ± 1.5	6.1 ± 1.4	0.59 ± 0.13	1.1 ± 0.14	0.91 ± 0.15	Ns	Ns	0.72 ± 0.09	1.4 ± 0.2
August 1974	1	12 ± 1.2	9.8 ± 0.6	0.99 ± 0.14	2.0 ± 0.15	0.43 ± 0.08	1.7 ± 0.4	Ns	1.1 ± 0.08	4.3 ± 0.2
August 1975	1	3.8 ± 0.9	5.1 ± 1.3	Ns	0.2 ± 0.08	Ns	0.89 ± 0.4	0.16 ± 0.09	0.75 ± 0.09	2.0 ± 0.3

*Aufwuchs samples were collected from Long Shot Pond and Mile Post 12 Creek, whereas the algae samples were collected from White Alice Inlet to Cannikin Lake.

†Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

‡Pre-Cannikin.

Table A.5—Gamma-Emitting Radionuclides in Lichens Collected at Amchitka Island

Location and date	No.	Gamma-emitting radionuclides,* pCi/g of dry weight									
		⁷ Be	⁴⁰ K	⁹⁵ Zr	⁹⁵ Nb	¹⁰³ Ru	¹⁰⁶ Ru	¹²⁵ Sb	¹³⁷ Cs	¹⁴⁴ Ce	¹⁵⁵ Eu
Composite from several sites (pre-Cannikin)											
1965	2	Na	Na	Na	Na	Na	11 ± 1.5	6.6 ± 0.1	38 ± 7	54 ± 7	Na
1966	2	Na	Na	Na	Na	Na	11 ± 2.5	7.8 ± 1.3	47 ± 7	54 ± 26	Na
1967†	4	Na	Na	Na	Na	Na	Na	Na	26 ± 3	Na	Na
1968†	4	Na	2.8 ± 0.6	Na	Na	Na	Na	1.5 ± 1.8	20 ± 9.6	4.5 ± 5.7	1.2 ± 0.8
1970†	9	Na	Na	1.4 ± 0.5	Na	Na	3.9 ± 1.7	0.88 ± 0.59	16 ± 7.3	11 ± 4	0.83 ± 0.48
Clam Lake											
1970–1971‡	7	15 ± 6.1	4.5 ± 6.4	1.0 ± 1.0	2.1 ± 1.9	1.5 ± 3.1	5.4 ± 3.2	5.6 ± 7.2	37 ± 39	Na	Na
1971–1972	5§	9.7 ± 8.2	6.2 ± 5.5	0.7 ± 0.7	1.7 ± 1.4	0.5 ± 0.7	3.6 ± 3.8	3.4 ± 3.5	27 ± 23	9 ± 0.4	1.5 ± 0.14
1973	3	5.3 ± 0.5	3.5 ± 0.3	0.03 ± 0.05	0.1 ± 0.1	0.03 ± 0.06	1.1 ± 0.2	0.60 ± 0.12	7 ± 6.9	3.7 ± 1.3	0.56 ± 0.32
May 1974	1	4.5 ± 0.9	2.4 ± 0.9	0.48 ± 0.09	1.2 ± 0.1	Ns	1.4 ± 0.5	0.56 ± 0.11	12 ± 0.3	4.0 ± 0.3	0.38 ± 0.05
August 1974	1	5.2 ± 1.2	3.7 ± 0.4	0.23 ± 0.18	0.9 ± 0.1	Ns	1.3 ± 0.4	0.33 ± 0.09	9 ± 0.2	4.1 ± 0.2	0.33 ± 0.09
August 1975	1	4.6 ± 1.7	2.5 ± 1.1	Ns	0.5 ± 0.1	Ns	1.0 ± 0.6	0.28 ± 0.14	6 ± 0.2	5.5 ± 0.4	0.23 ± 0.08
Ice Box Lake											
October 1972	1	Ns	2.8 ± 1.1	0.7 ± 0.1	1.4 ± 0.3	3.8 ± 2.0	Ns	2.6 ± 0.7	14 ± 0.2	Na	Na
1973	2	5.7 ± 0.3	0.6 ± 0.8	Ns	Ns	Ns	1.3 ± 0.1	0.86 ± 0.12	16 ± 0.7	4.3 ± 1.1	0.63 ± 0.18
May 1974	1	8.6 ± 1.1	1.4 ± 0.9	0.80 ± 0.12	2.1 ± 0.2	Ns	2.1 ± 0.5	0.59 ± 0.13	13 ± 0.3	8.1 ± 0.4	0.40 ± 0.06
August 1974	1	5.7 ± 1.5	1.3 ± 0.5	0.49 ± 0.19	0.8 ± 0.1	Ns	2.2 ± 0.5	0.64 ± 0.13	9 ± 0.2	6.0 ± 0.3	0.43 ± 0.07
August 1975	1	5.2 ± 1.5	1.9 ± 1.6	Ns	0.4 ± 0.1	Ns	1.5 ± 0.6	0.48 ± 0.14	11 ± 0.3	5.4 ± 0.3	0.38 ± 0.13
Cannikin Lake											
July 1972	1	5.3 ± 1.7	2.0 ± 0.7	0.7 ± 0.1	1.6 ± 0.1	0.6 ± 0.3	Ns	0.2 ± 0.4	21 ± 0.2	Na	Na
1973	2	5.3 ± 1.3	2.3 ± 0.1	Ns	Ns	0.07 ± 0.09	1.3 ± 0.1	0.90 ± 0.06	16 ± 0.7	4.1 ± 1.6	0.73 ± 0.17
May 1974	1	6.7 ± 0.6	1.6 ± 0.6	0.62 ± 0.07	1.6 ± 0.1	0.09 ± 0.06	1.6 ± 0.3	0.65 ± 0.08	11 ± 0.2	5.8 ± 0.2	0.39 ± 0.03
August 1974	1	5.1 ± 1.3	2.5 ± 0.6	0.30 ± 0.15	0.7 ± 0.1	Ns	1.7 ± 0.5	0.34 ± 0.12	8 ± 0.2	4.3 ± 0.3	0.30 ± 0.06
August 1975	1	6.1 ± 2.1	Ns	Ns	0.4 ± 0.2	Ns	1.4 ± 0.5	0.40 ± 0.10	7 ± 0.2	4.6 ± 0.3	0.26 ± 0.11

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

†Data from J. J. Koranda and J. R. Martin, 1973, Gamma-Emitting Radionuclides in Alaskan Environments, 1967–1970, in Proceedings of the Third National Symposium on Radioecology, Oak Ridge, Tenn., May 10–12, 1971, D. J. Nelson (Ed.), USAEC Report CONF-710501, pp. 81-107.

‡Pre-Cannikin.

§n equals 1 for ¹⁴⁴Ce and ¹⁵⁵Eu.

Table A.6—Potassium-40 and ^{137}Cs in Dolly Varden and Pink Salmon Collected at Amchitka Island

Collection date	Collection location	Tissue	No.†	Gamma-emitting radionuclides,* pCi/g of dry weight	
				⁴⁰ K	¹³⁷ Cs
Pink Salmon					
1971‡	Bering Sea	Muscle	1/1	15 ± 0.8	0.10 ± 0.05
1972	Bering Sea	Muscle	8/8	14 ± 3.1	Ns
August 1974	Chapel Cove stream	Muscle	1/1	15 ± 0.9	Ns
August 1974	Signal Cove stream	Muscle	1/1	15 ± 0.5	0.09 ± 0.03
Dolly Varden					
1965	Composite, several sites	Muscle	1/23	13§	2.3§
1966	Composite, several sites	Muscle	1/18	13§	2.2§
1971	Jones Lake	Muscle	1/1	15 ± 0.8	0.35 ± 0.05
1972	DK-45 Lake	Muscle	3/8	16 ± 1.0	5.7 ± 3.9
1973	Jones Lake	Muscle	1/2	16 ± 0.5	0.28 ± 0.03
1973	Bridge Creek	Muscle	1/1	15 ± 0.9	0.13 ± 0.06
1973	Silver Salmon outlet	Muscle	1/4	16 ± 0.4	0.13 ± 0.02
May 1974	Jones Lake	Muscle	1/5	14 ± 1.7	0.28 ± 0.05
August 1974	Cannikin Lake	Muscle	1/9	14 ± 0.5	0.31 ± 0.03
August 1974	Jones Lake	Muscle	3/10	13 ± 0.9	0.17 ± 0.10
August 1974	Duck Cove	Muscle	1/4	17 ± 0.5	0.35 ± 0.03
August 1975	Jones Lake	Muscle	1/5	4.4 ± 0.9	0.10 ± 0.03
August 1975	Cannikin Lake	Muscle	1/6	12 ± 1.6	0.25 ± 0.05
August 1975	Bridge Creek	Muscle	1/1	16 ± 2.2	0.33 ± 0.07
August 1975	Duck Cove Creek¶	Muscle	1/3	14 ± 1.7	0.10 ± 0.04
August 1975	Clevenger Creek¶	Muscle	1/4	13 ± 1.7	0.05 ± 0.04

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Ns, not significant.

†Number of pooled samples/total number of fish in all samples.

‡Pre-Cannikin.

§No counting error given in original publication (Seymour and Nakatani, 1967).

¶Collected from the intertidal area at the mouths of these streams.

Table A.7—Potassium-40 and ^{137}Cs in Halibut Collected off Amchitka Island

Location and date	Tissue	No.†	Gamma-emitting radionuclides,* pCi/g of dry weight	
			⁴⁰ K	¹³⁷ Cs
Bering Sea off C Site				
1971‡	Muscle	4/4	18 ± 1.7	0.06 ± 0.08
1971–1972	Muscle	9/9	17 ± 1.7	0.02 ± 0.03
1973	Muscle	5/5	18 ± 1.1	0.11 ± 0.02
August 1975	Muscle	1/1	18 ± 1.6	0.06 ± 0.04
1971‡	Liver	4/4	13 ± 5.9	0.27 ± 0.28
1971–1972	Liver	8/8	6.7 ± 2.1	Ns
1973	Liver	5/5	6.9 ± 1.3	0.04 ± 0.05
August 1975	Liver	1/8	11 ± 1.5	0.05 ± 0.03
Constantine Harbor				
August 1967‡	Muscle	2/2	15 ± 0.6	0.06 ± 0.08
August 1974§	Liver	5/5	7.5 ± 2.6	0.06 ± 0.07
Midden Cove				
August 1975	Muscle	2/2	19 ± 1.9	0.05 ± 0.04
August 1975	Liver	4/4	10 ± 1.5	Ns

*Values are given as the mean $\pm$ one standard deviation. Ns, not significant; i.e., all the net sample counts in that group were less than their two-sigma, propagated, counting errors.

†Number of pooled samples/total number of fish in all samples.

‡Pre-Cannikin.

§Cobalt-60 was present (0.03 ± 0.02 pCi/g of dry weight) in one liver sample.

Table A.8—Potassium-40 and ^{137}Cs in Rock Ptarmigan and Sea Otters Collected at Amchitka Island

Collection date	Collection location	Tissue	No.	Radionuclides,* pCi/g of dry weight	
				⁴⁰ K	¹³⁷ Cs
Ptarmigan					
1970–1971†	South Bight	Muscle	4	11 ± 0.5	1.0 ± 0.6
1971–1972	C Site	Muscle	3	11 ± 1.6	0.70 ± 0.04
1973	‡	Muscle	5	11 ± 0.8	0.43 ± 0.25
May 1974	C Site	Muscle	2	11 ± 1.2	0.42 ± 0.05
August 1974	C Site	Muscle	4	11 ± 1.5	0.90 ± 0.35
August 1975	C Site	Muscle	4	14 ± 2	3.4 ± 0.2
August 1975	Mile 8	Muscle	2	11 ± 2	1.4 ± 0.1
August 1975	Milrow area	Muscle	2	12 ± 2	1.8 ± 0.6
1970–1971†	South Bight	Liver	1	Ns	Ns
August 1974	C Site	Viscera	4	13 ± 1.2	1.6 ± 0.8
Sea Otters					
February 1971		Liver	1	8.6 ± 1.1	0.27 ± 0.08
February 1971		Skin	1	1.1 ± 0.9	Ns
February 1971		Kidney	1	9.8 ± 1.0	Ns
February 1971		Muscle	1	10 ± 0.5	Ns
April 1973	Duck Cove	Muscle	1	6.8 ± 0.3	Ns
April 1973	Duck Cove	Liver	1	6.7 ± 0.5	Ns

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Ns, not significant.

†Pre-Cannikin.

‡One each from Mason Lake, C Site, and Mile Post 16; two from Mile Post 5.

Table A.9—Potassium-40 and ^{137}Cs in Greenling
Collected off Amchitka Island

Location and date	Tissue	No.†	Gamma-emitting radionuclides,* pCi/g of dry weight	
			^{40}K	^{137}Cs
Composite, several sites				
1965	Muscle	1/13	11‡	0.13‡
1965	Viscera	1/13	3.8‡	Ns
Cyril Cove				
1967	Muscle	2/38	17 ± 0.9	0.13 ± 0.01
1967	Liver	1/38	8.5‡	Ns
Constantine Harbor				
1967	Entire (less viscera)	1/1	11‡	0.06‡
1971§	Muscle	2/19	16 ± 0.7	0.37 ± 0.42
1971–1972	Muscle	15/29	15 ± 1.3	0.04 ± 0.04
1973	Muscle	2/9	17 ± 2.8	0.05 ± 0.06
May 1974	Muscle	1/5	18 ± 1.5	0.06 ± 0.03
August 1974	Muscle	1/5	16 ± 0.8	0.07 ± 0.05
August 1975	Muscle	1/4	21 ± 2.5	0.49 ± 0.07
1971§	Viscera	2/19	13 ± 0.7	0.15 ± 0.05
December 1971	Liver	1/10	13 ± 1.6	0.21 ± 0.12
1973	Viscera	1/4	9.1 ± 0.6	Ns
May 1974	Viscera	1/5	15 ± 1.0	0.03 ± 0.02
August 1974	Viscera	1/5	9.2 ± 0.8	Ns
August 1975	Viscera	1/4	11 ± 2.2	0.06 ± 0.05
Sand Beach Cove				
1971§	Muscle	3/27	15 ± 1.2	0.07 ± 0.02
1971–1972	Muscle	15/26	15 ± 1.6	0.03 ± 0.05
1973	Muscle	2/12	17 ± 1.4	0.05 ± 0.06
May 1974	Muscle	1/5	21 ± 1.9	0.05 ± 0.04
August 1974¶	Muscle	1/4	15 ± 0.7	Ns
August 1975	Muscle	1/8	25 ± 2.7	0.08 ± 0.06
1971§	Viscera	3/27	13 ± 0.6	0.02 ± 0.02
1972	Liver	1/6	21 ± 2.9	Ns
1973	Viscera	1/6	11 ± 0.4	Ns
May 1974	Viscera	1/5	9.1 ± 1.1	Ns
August 1974	Viscera	1/4	8.1 ± 2.1	Ns
August 1975	Viscera	1/8	6.3 ± 1.4	0.06 ± 0.04
Square Bay				
August 1975	Muscle	1/5	16 ± 1.6	Ns
August 1975	Viscera	1/5	7.8 ± 1.4	0.07 ± 0.04
Duck Cove				
1972	Muscle	8/14	16 ± 1.1	0.06 ± 0.06
1973	Muscle	2/8	15 ± 2.8	0.08 ± 0.01
May 1974	Muscle	1/3	18 ± 1.6	0.06 ± 0.03
August 1974**	Muscle	2/6	15 ± 1.8	0.07 ± 0.02
August 1975	Muscle	1/6	17 ± 1.8	0.09 ± 0.04
1973	Viscera	1/4	12 ± 0.5	0.13 ± 0.03
May 1974	Viscera	1/3	7.7 ± 0.8	0.04 ± 0.02
August 1974	Viscera	2/6	9.5 ± 0.1	0.15 ± 0.05
August 1975	Viscera	1/6	9.5 ± 1.2	0.04 ± 0.03

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Ns, not significant.

†Number of pooled samples/total number of fish in all samples.

‡Counting errors were not given in the original publication (Seymour and Nakatani, 1967).

§Pre-Cannikin.

¶Cobalt-60 (0.07 ± 0.04 pCi/g of dry weight) was also detected in this sample.

**Cobalt-60 (0.03 ± 0.02 pCi/g of dry weight) was also detected in this sample.

Table A.10—Iron-55 in Fish Collected at Amchitka Island

Species and tissue	Collection year	No.*	pCi ⁵⁵ Fe/g of dry weight†	pCi ⁵⁵ Fe/mg Fe
Halibut				
Muscle	1969–1970	2/27	0.21 ± 0.14	11 ± 1.8
Muscle	1972	2/2	0.36 ± 0.11	8.7 ± 2.6
Muscle	1973	2/2	0.09 ± 0.10	2.7 ± 2.3
Liver	1970	2/27	2.5 ± 0.03	13 ± 0.7
Liver	1972	2/2	3.1 ± 0.08	26 ± 7.1
Liver	1973	2/2	0.54 ± 0.37	5.3 ± 2.1
Liver	1974	2/2	2.2 ± 0.33	6.7 ± 2.4
Greenling				
Muscle	1970	5/60	0.75 ± 0.74	12 ± 6.7
Muscle	1972	3/20	0.09 ± 0.07	1.1 ± 0.5
Muscle	1973	3/15	0.04 ± 0.02	1.8 ± 1.0
Muscle	1974	4/17	0.09 ± 0.07	4.5 ± 1.8
Liver	1970	5/60	8.3 ± 6.3	13 ± 11
Liver	1973	3/15	1.4 ± 1.5	0.7 ± 0.3
Viscera	1974	4/17	0.37 ± 0.18	0.2 ± 0.1
Pink Salmon				
Muscle	1969	2/2	6.7 ± 4.3	93 ± 6.6
Muscle	1972	4/4	0.61 ± 0.30	18 ± 2.8
Muscle	1974	2/2	0.39 ± 0.04	11 ± 1.5
Liver	1969–1970	3/3	57 ± 2.7	82 ± 24
Liver	1972	1/8	15 ± 0.1	21 ± 1.1
Viscera	1974	1/1	13 ± 0.1	13 ± 0.7
Dolly Varden				
Muscle	1969–1970	3/33	0.91 ± 1.0	50 ± 59
Muscle	1972	2/2	0.36 ± 0.18	9.1 ± 5.0
Muscle	1973	1/4	0.05 ± 0.01	1.6 ± 0.1
Muscle	1974	4/19	0.06 ± 0.03	2.3 ± 0.5
Liver	1969–1970	3/29	7.2 ± 5.0	47 ± 44‡
Liver	1973	1/4	2.1 ± 0.1	1.9 ± 0.1
Viscera	1974	4/19	0.35 ± 0.22	0.43 ± 0.23

*Number of pooled samples/total number of fish in all samples.

†Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean.

‡n equals 2/11 since there was no stable iron value for one group of 18 fish.

Table A.11—Some Gamma-Emitting Radionuclides in Green Sponge Collected at Amchitka Island

Location and date	No.	Gamma-emitting radionuclides, * pCi/g of dry weight				
		⁷ Be	⁴⁰ K	⁹⁵ Zr	⁹⁵ Nb	¹⁴⁴ Ce
Duck Cove						
1971–1972	4	2.7 ± 2.7	11 ± 3	0.05 ± 0.07	0.11 ± 0.14	Na
1973	2	1.5 ± 0.6	9.8 ± 0.1	Ns	Ns	0.42 ± 0.04
May 1974	1	1.0 ± 0.4	10 ± 1.5	0.16 ± 0.07	0.36 ± 0.07	1.1 ± 0.17
August 1974	1	Ns	7.2 ± 1.3	Ns	Ns	1.2 ± 0.23
August 1975	1	Ns	7.7 ± 1.4	Ns	Ns	0.73 ± 0.20
Sand Beach Cove						
June 1972	1	Ns	6.8 ± 1.7	0.24 ± 0.13	0.54 ± 0.28	Na
April 1973	1	Ns	12 ± 1.7	Ns	Ns	0.31 ± 0.17
May 1974	1	1.1 ± 0.4	9.0 ± 1.5	0.10 ± 0.07	0.26 ± 0.07	0.60 ± 0.16
August 1974	1	Ns	9.6 ± 1.4	Ns	Ns	1.2 ± 0.2
August 1975	1	Ns	10.0 ± 1.6	Ns	Ns	0.56 ± 0.2
Square Bay						
1973	2	0.7 ± 0.9	9.7 ± 0.5	Ns	Ns	0.35 ± 0.12
August 1975	1	1.2 ± 0.9	9.5 ± 1.7	Ns	0.11 ± 0.09	0.61 ± 0.20

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

Table A.12—Some Gamma-Emitting Radionuclides on Air Filters at Ground Level at the Amchitka Island Base Camp

Collection period	No.†	Mean volume, 10 ³ m ³	Gamma-emitting radionuclides, * fCi/m ³					
			⁷ Be	⁹⁵ Zr	⁹⁵ Nb	¹⁰³ Ru	¹³⁷ Cs	¹⁴⁴ Ce
Pre-Cannikin								
1970–1971	28	24.5 ± 3.7	20 ± 9	2.8 ± 2.1	5.9 ± 4.5	0.7 ± 1.1	0.7 ± 0.3	Na
Post-Cannikin								
1972	45	11.3 ± 1.6	17 ± 11	0.7 ± 1.2	1.3 ± 1.6	0.37 ± 0.59	0.24 ± 0.24	Na
1973	34	11.1 ± 1.4	16 ± 10	Ns	0.04 ± 0.09	0.04 ± 0.07	0.16 ± 0.13	0.42 ± 0.53
1974	1	~3	Ns	Ns	Ns	Ns	Ns	Ns

*Single-sample errors are two-sigma, propagated, counting errors, whereas the error shown for more than one sample is one standard deviation of the mean. Na, not analyzed; Ns, not significant.

†Number of pooled samples.

Table A.13—Gamma-Emitting Radionuclides in Samples Collected with a Filter and Sorption Bed System from Intertidal Areas of Amchitka Island

Location and date	Liters sampled	Fraction	No.	Gamma-emitting radionuclides,* pCi/liter			
				⁷ Be	⁹⁵ Zr	⁹⁵ Nb	¹³⁷ Cs
Constantine Harbor							
1970–1971†	2590 ± 1800	Particulate	6	0.009 ± 0.011	0.002 ± 0.008	0.006 ± 0.007	0.001 ± 0.001
1970–1971	2590 ± 1800	Soluble	6	0.38 ± 0.81	0.003 ± 0.017	0.012 ± 0.015	0.002 ± 0.035
1971–1972	730 ± 600	Particulate	5	Ns	0.001 ± 0.002	0.003 ± 0.006	0.02 ± 0.02
1971–1972	730 ± 600	Soluble	5	0.14 ± 0.21	0.002 ± 0.004	0.004 ± 0.009	0.02 ± 0.04
1973	1280 ± 770	Particulate	2	Ns	Ns	Ns	Ns
1973	1280 ± 770	Soluble	2	Ns	Ns	Ns	Ns
May 1974‡	534	Particulate	1	Ns	0.006 ± 0.005	0.009 ± 0.003	Ns
May 1974	534	Soluble	1	Ns	Ns	Ns	Ns
August 1974	1134	Particulate	1	Ns	Ns	Ns	Ns
August 1974	1134	Soluble	1	Ns	Ns	Ns	Ns
Duck Cove							
1971†	660 ± 380	Particulate	2	0.018 ± 0.025	0.004 ± 0.005	0.008 ± 0.011	Ns
1971†	660 ± 380	Soluble	2	Ns	0.002 ± 0.002	0.003 ± 0.004	Ns
1971–1972	305 ± 182	Particulate	6	0.032 ± 0.078	0.001 ± 0.002	0.002 ± 0.005	0.005 ± 0.008
1971–1972	305 ± 182	Soluble	6	Ns	0.002 ± 0.005	0.005 ± 0.011	Ns
1973	544 ± 557	Particulate	2	Ns	Ns	Ns	Ns
1973	544 ± 557	Soluble	2	Ns	Ns	Ns	Ns
May 1974§	98	Particulate	1	Ns	Ns	0.046 ± 0.025	0.016 ± 0.014
May 1974§	98	Soluble	1	Ns	Ns	Ns	Ns
August 1974	437	Particulate	1	Ns	Ns	0.036 ± 0.013	Ns
August 1974	437	Soluble	1	Ns	Ns	Ns	Ns
Sand Beach Cove							
1971–1972	494 ± 233	Particulate	6	Ns	0.004 ± 0.006	0.008 ± 0.013	0.003 ± 0.004
1971–1972	494 ± 233	Soluble	6	0.072 ± 0.18	Ns	Ns	0.003 ± 0.007
1973	462 ± 310	Particulate	2	Ns	Ns	Ns	Ns
1973	462 ± 310	Soluble	2	Ns	Ns	Ns	Ns
May 1974¶	314	Particulate	1	Ns	Ns	0.028 ± 0.010	Ns
May 1974	314	Soluble	1	Ns	Ns	Ns	Ns
August 1974	310	Particulate	1	Ns	Ns	Ns	Ns
August 1974	310	Soluble	1	Ns	Ns	Ns	Ns

*Single-sample error values are two-sigma, propagated, counting errors, whereas the value given for more than one sample is the mean ± one standard deviation. Ns, not significant.

†Pre-Cannikin.

‡Cerium-144 was also present, 0.014 ± 0.008 pCi/liter.

§Cerium-144 was also present, 0.13 ± 0.07 pCi/liter.

¶Cerium-144 was also present, 0.035 ± 0.024 pCi/liter.

Table A.14—Gamma-Emitting Radionuclides in Water Samples Collected from Lakes on Amchitka Island

Location and date	Liters sampled	Fraction	No.	Gamma-emitting radionuclides,* pCi/liter			
				⁷ Be	⁹⁵ Zr	⁹⁵ Nb	¹³⁷ Cs
Jones Lake							
1971†	278 ± 240	Particulate	4	Ns	0.05 ± 0.04	0.11 ± 0.08	0.02 ± 0.04
1971	278 ± 240	Soluble	4	Ns	0.01 ± 0.01	0.02 ± 0.02	0.02 ± 0.02
1971–1972	154 ± 103	Particulate	5	0.2 ± 0.3	0.008 ± 0.011	0.02 ± 0.02	0.004 ± 0.009
1971–1972	154 ± 103	Soluble	5	1.3 ± 2.9	0.07 ± 0.15	0.16 ± 0.33	0.05 ± 0.10
1973	172 ± 30	Particulate	2	Ns	Ns	Ns	0.042 ± 0.015
1973	172 ± 30	Soluble	2	Ns	Ns	Ns	Ns
May 1974‡	53	Particulate	1	Ns	0.084 ± 0.062	0.19 ± 0.06	0.039 ± 0.029
May 1974‡	53	Soluble	1	Ns	Ns	Ns	Ns
August 1974	413	Particulate	1	Ns	Ns	Ns	Ns
August 1974	413	Soluble	1	Ns	Ns	Ns	Ns
August 1975	56	Entire	1	1.1 ± 0.3	Ns	0.05 ± 0.03	0.12 ± 0.03
Lake DK-45							
1971–1972	148 ± 133	Particulate	5	0.16 ± 0.22	0.07 ± 0.09	0.15 ± 0.20	0.07 ± 0.15
1971–1972	148 ± 133	Soluble	5	4 ± 9	Ns	Ns	Ns
1973	110 ± 57	Particulate	2	Ns	Ns	Ns	0.07 ± 0.05
1973	110 ± 57	Soluble	2	Ns	Ns	Ns	Ns
May 1974§	170	Particulate	1	0.33 ± 0.16	0.23 ± 0.04	0.47 ± 0.05	Ns
May 1974§	170	Soluble	1	Ns	0.20 ± 0.17	0.24 ± 0.13	Ns
August 1974	174	Particulate	1	Ns	Ns	Ns	Ns
August 1974	174	Soluble	1	Ns	Ns	Ns	Ns
Heart Lake							
August 1975	52	Entire	1	2.3 ± 0.4	0.09 ± 0.05	0.15 ± 0.04	0.25 ± 0.04
Cannikin Lake							
1972	9 ± 1.4	Particulate	2	Ns	0.17 ± 0.23	0.34 ± 0.48	Ns
1973	84 ± 16	Particulate	2	Ns	Ns	Ns	0.04 ± 0.057
1973	84 ± 16	Soluble	2	Ns	Ns	Ns	0.08 ± 0.11
May 1974¶	314	Particulate	1	Ns	0.20 ± 0.04	0.25 ± 0.03	0.019 ± 0.013
May 1974¶	314	Soluble	1	Ns	Ns	Ns	Ns
August 1974	99	Particulate	1	Ns	Ns	Ns	Ns
August 1974	99	Soluble	1	Ns	Ns	Ns	Ns
August 1975	53	Entire	1	Ns	Ns	Ns	0.21 ± 0.04
Long Shot Mud Pit No. 1							
1970–1971†	418 ± 398	Particulate	6	4.0 ± 4.7	0.4 ± 0.6	0.9 ± 1.2	0.02 ± 0.03
1970–1971	418 ± 398	Soluble	6	11 ± 18	0.002 ± 0.003	0.006 ± 0.009	0.08 ± 0.18
1971–1972	56 ± 41	Particulate	5	1.2 ± 1.3	0.25 ± 0.29	0.48 ± 0.55	0.03 ± 0.07
1971–1972	56 ± 41	Soluble	5	0.44 ± 0.98	Ns	Ns	Ns
1973	35 ± 5	Particulate	2	2.0 ± 1.0	Ns	Ns	0.04 ± 0.06
1973	35 ± 5	Soluble	2	Ns	Ns	Ns	Ns
May 1974**	48	Particulate	1	4.0 ± 0.7	1.3 ± 0.1	2.7 ± 0.2	0.034 ± 0.028
May 1974	48	Soluble	1	Ns	Ns	Ns	Ns
August 1974	189	Particulate	1	0.7 ± 0.2	0.06 ± 0.03	0.14 ± 0.02	Ns
August 1974	189	Soluble	1	Ns	Ns	0.21 ± 0.10	Ns
August 1975††	50	Entire	1	1.2 ± 0.3	Ns	Ns	0.08 ± 0.03

*Single-sample error values are two-sigma, propagated, counting errors, whereas the value given for more than one sample is the mean ± standard deviation. Ns, not significant.

†Pre-Cannikin.

‡Cerium-144 was also present, 0.44 ± 0.14 pCi/liter.

§Ruthenium-106 (0.45 ± 0.25 pCi/liter), ¹²⁵Sb (0.09 ± 0.06 pCi/liter), and ¹⁴⁴Ce (0.24 ± 0.11 pCi/liter) were also present in this sample.

¶Cerium-144 was also present, 0.41 ± 0.07 pCi/liter.

**Cerium-144 was also present 4.9 ± 0.3 pCi/liter.

††Barium-140 was also present, 0.43 ± 0.37 pCi/liter.

Table A.15—Gamma-Emitting Radionuclides in Sand and Soil
Collected at Amchitka Island in August 1975

Sample type	Collection location	Gamma-emitting radionuclides,* pCi/g of dry weight				
		⁴⁰ K	¹³⁷ Cs	¹⁴¹ Ce	¹⁴⁴ Ce	Other†
Soil	Main camp	8.0 ± 1.2	Ns	0.20 ± 0.13	0.14 ± 0.13	Ns
Soil	Cannikin area	11 ± 1.3	0.32 ± 0.05	0.22 ± 0.15	0.97 ± 0.18	‡
Sand	Constantine Harbor	13 ± 1.2	0.07 ± 0.03	Ns	Ns	Ns
Sand	Sand Beach Cove	9.8 ± 1.1	0.06 ± 0.03	Ns	0.2 ± 0.1	Ns

*Errors are two-sigma, propagated, counting errors for a single sample. Ns, not significant.

†Radium-226, ²²⁸Th, and ²³⁸U in the sand samples and ²²⁶Ra and ²²⁸Th in the soil samples were present in concentrations of less than 0.5 pCi/g of dry weight.

‡Zirconium-95 (0.16 ± 0.14 pCi/g of dry weight), ⁹⁵Nb (0.18 ± 0.07 pCi/g of dry weight) and ¹⁰⁶Ru (0.42 ± 0.30 pCi/g of dry weight) were also present in this sample.

Table A.16—Radiation Survey of Selected Sites on Amchitka Island

Location	Radiation level,* mR/hr			
	Average reading		Maximum reading	
	August 1974	August 1975	August 1974	August 1975
Decon Facility	0.01	0.01	0.05	0.04
Inside "D" barracks	0.01	<0.01	0.04	0.04
Hus-Key Camp	<0.01	0.01	0.04	0.05
Jones Creek effluence	<0.01	<0.01	0.04	0.04
Eberline Instrument Corp.				
Calibration Range	<0.01	0.01	0.04	0.04
Rifle Range target area	0.01	0.01	0.04	0.05
Duck Cove	<0.01	<0.01	0.03	0.04
Milrow surface ground				
zero and vicinity	<0.01	0.01	0.04	0.04
Long Shot surface ground				
zero and vicinity	0.01	0.01	0.05	0.05
Cannikin surface ground				
zero and vicinity	0.01	0.01	0.04	0.04
Cannikin drillback	0.01	0.01	0.05	0.04
Sand Beach Cove	<0.01	<0.01	0.04	0.04
D Site	0.01	<0.01	0.05	0.03
E Site	0.01	<0.01	0.03	0.04

*Geiger-Mueller detector, probe window thickness less than 2 mg/cm².

Table A.17—Tritium Concentration in Water Samples Collected at Amchitka Island, 1970–1975

Date	Collection site	Number of samples	Tritium units*	pCi/liter†
Seawater				
1970–1971‡		10	32 ± 19	103 ± 61
1972		16	28 ± 25	90 ± 81
1973		6	22 ± 13	71 ± 42
1974		6	<13	<42
1975		6	<15	<48
August 1975	Constantine Harbor	1	18 ± 12	57 ± 40
August 1975	Square Bay	1	17 ± 12	56 ± 40
August 1975	Sand Beach Cove	1	<13	<42
August 1975	Makarius Bay	1	<13	<42
August 1975	Rifle Range Point	1	<13	<42
August 1975	Duck Cove	1	<13	<42
Freshwater, except Long Shot Area				
1970–1971‡		12	92 ± 46	298 ± 149
1972		18	49 ± 14	158 ± 45
1973		46	50 ± 17	162 ± 55
1974		44	32 ± 18	103 ± 58
1975		29	34 ± 14	110 ± 45
August 1975	South Hangar (ppt)	1	33 ± 13	106 ± 43
August 1975	Constantine Spring	1	56 ± 13	182 ± 41
August 1975	Jones Lake outlet	1	28 ± 12	89 ± 40
August 1975	Clevenger Lake outlet	1	51 ± 13	165 ± 41
August 1975	Clevenger Creek (mouth)	1	30 ± 12	98 ± 40
August 1975	Clevenger Creek (headwaters)	1	26 ± 12	84 ± 40
August 1975	Heart Lake	1	<13	<42
August 1975	Clam Lake	1	24 ± 12	78 ± 38
August 1975	Duck Cove Creek (mouth)	1	41 ± 13	132 ± 38
August 1975	Seep at Duck Cove	1	47 ± 13	151 ± 41
August 1975	Quonset Creek (at road)	1	24 ± 13	78 ± 43
August 1975	Bridge Creek (at road)	1	55 ± 13	177 ± 41
August 1975	Mile Post 12 Creek	1	40 ± 12	129 ± 38
August 1975	Cannikin Lake inlet from ground zero	1	<13	<42
August 1975	Cannikin Lake inlet from drillback	1	53 ± 13	173 ± 41
August 1975	Cannikin Lake White Alice inlet	1	41 ± 13	133 ± 41
August 1975	Cannikin Lake Station No. 1 surface	1	21 ± 10	67 ± 33
August 1975	Cannikin Lake Station No. 1 bottom	1	27 ± 10	87 ± 34
August 1975	Cannikin Lake Station No. 2 surface	1	<13	<42
August 1975	Cannikin Lake Station No. 2 bottom	1	38 ± 12	124 ± 38
August 1975	Cannikin Lake Station No. 3 surface	1	47 ± 11	151 ± 34
August 1975	Cannikin Lake Station No. 3 bottom	1	36 ± 10	115 ± 34
August 1975	Cannikin Lake Station No. 4 surface	1	46 ± 11	148 ± 34
August 1975	Cannikin Lake Station No. 4 bottom	1	33 ± 10	108 ± 34
August 1975	Cannikin Lake outlet	1	19 ± 12	63 ± 40
August 1975	Ice Box Lake inlet¶	1	31 ± 12	102 ± 40
August 1975	Ice Box Lake outlet¶	1	57 ± 13	183 ± 41
August 1975	DK-45 Lake	1	<13	<42
August 1975	Seep-Sand Beach Cove	1	45 ± 13	144 ± 41
Long Shot Mud Pits				
1970–1971‡	Mud Pit No. 3	3	3500 ± 460	11300 ± 1500

(Table continues on page 612.)

Table A.17—(Continued)

Date	Collection site	Number of samples	Tritium units*	pCi/liter†
1974	Mud Pit No. 3	1	2900 ± 460	9400 ± 160
August 1975	Mud Pit No. 3	1	867 ± 19	2802 ± 61
1970–1971‡	Mud Pit No. 1	3	1800 ± 260	5800 ± 840
1972	Mud Pit No. 1	4	2050 ± 240	6600 ± 780
1973	Mud Pit No. 1	2	1900 ± 420	6100 ± 1400
1974	Mud Pit No. 1	2	1300 ± 250	4200 ± 810
August 1975	Mud Pit No. 1	1	122 ± 11	395 ± 36
Long Shot Mud Pit drainage				
August 1975	3 m below Mud Pit No. 1	1	872 ± 19	2817 ± 61
August 1975	Infantry Road	1	666 ± 16	2153 ± 52
August 1975	100 m below road	1	424 ± 15	1369 ± 47
August 1975	500 m below road	1	82 ± 13	264 ± 42
August 1975	200 m above Square Bay	1	121 ± 13	390 ± 44
August 1975	Mouth of creek	1	107 ± 13	347 ± 43

*The error shown for single samples is a one-sigma counting error, whereas the error for more than one sample is the one-standard deviation of the mean.

†One TU equals 3.23 pCi/liter.

‡Pre-Cannikin.

§Mean value for all collection sites.

¶A small lake formed in the north fork of White Alice Creek after surface subsidence occurred at the Cannikin site.

Table A.18—Tritium Concentration in Tissue-Water Hydrogen (TWH) and Tissue-Bound Hydrogen (TBH) from Biological Samples Collected at Amchitka Island in August 1975

Organism	Tissue	Collection site	No.*	Tritium units†		pCi/liter†		Ratio TBH/TWH
				TWH	TBH	TWH	TBH	
<i>Fucus</i>	Entire	Constantine Harbor	2	<35 ± 18	167 ± 14	<113 ± 58	539 ± 45	>4.8
<i>Fucus</i>	Entire	Square Bay	3	<26 ± 12	49 ± 12	<84 ± 39	158 ± 39	>1.9
<i>Fucus</i>	Entire	Sand Beach Cove	2	<21 ± 1	49 ± 12	<68 ± 3	158 ± 39	>2.3
Greenling	Muscle	Constantine Harbor	1	<14	52 ± 18	<45	168 ± 58	>3.7
Greenling	Muscle	Square Bay	4	<20 ± 2	63 ± 12	<65 ± 6	203 ± 39	>3.2
Greenling	Muscle	Sand Beach Cove	2	<20 ± 1	80 ± 19	<65 ± 3	258 ± 61	>4.0
Dolly Varden	Muscle	Bridge Creek‡	2	16 ± 2	73 ± 11	51 ± 6	235 ± 36	4.6
Dolly Varden	Muscle	Jones Lake	4	26 ± 16	81 ± 11	85 ± 52	261 ± 37	3.1
Dolly Varden	Muscle	Cannikin Lake	1	39 ± 12	92 ± 12	126 ± 39	297 ± 39	2.4
<i>Fontinalis</i>	Entire	White Alice Creek	2	39 ± 28	180 ± 13	126 ± 91	580 ± 40	4.6
<i>Fontinalis</i>	Entire	Long Shot drainage	2	85 ± 14	248 ± 20	275 ± 45	801 ± 65	2.9

*Number of free water samples from a single tissue sample.

†The error term for single samples (all bound samples plus free samples where n equals 1) is a one-sigma counting error, whereas the error for free samples where n is greater than 1 is one standard deviation of the mean.

‡Intertidal area at the mouth of the creek.

Table A.19—Strontium-90 in Bone from Rats and Ptarmigan and in Soil Collected at Amchitka Island

Collection date	Location	Sample type	pCi ⁹⁰ Sr/g of dry weight*
October 1971†	Sand Beach Cove	Rat, bone	0.7 ± 0.2
October 1971†	Sand Beach Cove	Rat, bone	2.5 ± 0.2
December 1971	Sand Beach Cove	Rat, bone	10.1 ± 0.4
December 1971	Sand Beach Cove	Rat, bone	1.6 ± 0.2
April 1973	Sand Beach Cove	Rat, bone	1.9 ± 0.5
August 1973	Main dump	Rat, bone	1.8 ± 0.1
August 1974	Main dump	Rat, bone	0.8 ± 0.7
August 1974	Duck Cove	Rat, bone	2.3 ± 0.7
August 1975	Constantine Harbor	Rat, bone	1.6 ± 0.8
August 1975	Duck Cove	Rat, bone	1.2 ± 0.9
August 1975	Sand Beach Cove	Rat, bone	0.5 ± 0.1
November 1971†	Clevenger Creek	Ptarmigan, bone	27.0 ± 0.8
November 1971†	Baker Runway	Ptarmigan, bone	35.2 ± 1.0
December 1971	Base Camp	Ptarmigan, bone	18.3 ± 0.5
December 1971	C Site	Ptarmigan, bone	30.7 ± 0.9
August 1973	Silver Salmon Lake	Ptarmigan, bone	13.9 ± 0.2
September 1973	Clam Lake	Ptarmigan, bone	11.0 ± 0.2
August 1974	Mile Post 8	Ptarmigan, bone	16.1 ± 2.3
August 1975	Milrow Area	Ptarmigan, bone	13.8 ± 0.7
August 1975	Mile Post 8	Ptarmigan, bone	19.2 ± 1.4
August 1975	Cannikin Area	Ptarmigan, bone	12.5 ± 0.5
August 1975	Main Camp	Soil	0.03 ± 0.01
August 1975	Cannikin Area	Soil	<0.16

*Errors are one-sigma, propagated, counting errors for a single sample.

†Pre-Cannikin.

Table A.20—Plutonium-239,240 in *Fucus*, Greenling, Sand, and Soil Collected at Amchitka Island in August 1975

Sample type	Collection location	pCi/g of dry weight*	dpm/kg of wet weight
<i>Fucus</i> , entire	Sand Beach Cove	0.006 ± 0.001	3.0 ± 0.5
<i>Fucus</i> , entire	Constantine Harbor	0.002 ± 0.001	0.7 ± 0.4
Greenling, muscle	Sand Beach Cove	<0.002	<0.8
Greenling, muscle	Constantine Harbor	<0.003	<1.2
Sand, surface†	Sand Beach Cove	0.004 ± 0.001	
Sand, surface	Constantine Harbor	<0.002	
Soil, surface	Cannikin Area	0.015 ± 0.002	
Soil, surface	Main Camp	0.001 ± 0.001	

*Errors are one-sigma, propagated, counting errors for a single sample.

†Surface samples were the 0- to 2.5-cm layer.

Polychlorinated Biphenyls in the Ecosystems

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Chemical residues in the form of DDE and polychlorinated biphenyls (PCB) from 21 species taken from Amchitka environs between 1970 and 1974 were identified and quantified. These samples were from birds, mammals, and fish and represented carnivores, herbivores, and omnivores, and both the aquatic and terrestrial ecosystems. The levels of DDE and PCB were then compared with ecological equivalents of the same or similar species in other parts of the Aleutians and Pacific Basin. The Amchitka samples

generally had higher residue levels than ecological equivalents in the Southern Hemisphere, and carnivores were generally higher than other types. The sources of these pollutants found in the Amchitka region are discussed. Current levels of DDE and PCB are not high enough in the Amchitka ecosystem to be of prime concern or to impair reproduction. They are, however, higher than would be expected for the remoteness of the island from sources of pollutants and bear careful monitoring.

Polychlorinated biphenyls (PCB), a class of industrial synthetic chemicals, have become ubiquitous contaminants in marine environments (Jensen et al., 1969; Koeman et al., 1969; Risebrough et al., 1968; 1972; Risebrough and Carmignani, 1972; Risebrough and de Lappe, 1972; Harvey et al., 1974). The chemistry of the PCB has recently been reviewed by Hutzinger, Safe, and Zitko (1974); production and use data have been presented by Nisbet and Sarofim (1972), the Panel on Hazardous Trace Substances (1972), and Peakall (1975); Peakall (1975) has reviewed studies of the environmental effects of PCB. The amounts of PCB transferred to the environment and the rates of transfer have been estimated by Nisbet and Sarofim (1972) and by the Panel on Hazardous Trace Substances (1972).

This chapter examines the presence of PCB in ecosystems of Amchitka Island to (1) determine as far as possible their present levels in representative species; (2) determine whether the observed distribution of PCB suggests local input from human activities, atmospheric input from distant sources, or transport to Amchitka in ocean currents; (3) compare levels within Amchitka ecosystems with those of other ecosystems in the Pacific basin; and (4) assess potential impact on the local environment.

Waste-water outfalls and the dumping of sewage sludge in coastal areas introduce large quantities of PCB to the marine environment (Schmidt, Risebrough, and Gress, 1971; Holden, 1970;

Young et al., in press). Rivers also constitute an input. In southern California, however, the amounts of PCB entering the sea from rivers have been small relative to the input from waste-water outfalls. Trichlorinated and tetrachlorinated biphenyls predominate in these waste waters (Young et al., in press). Many data also indicate that PCB enters the sea from the atmosphere. Bidleman and Olney (1974a; 1974b) and Harvey and Steinhauer (1974) have measured PCB in the atmosphere over the North Atlantic. The decrease in atmospheric concentration of PCB from near shore to open ocean was approximately exponential with distance (Harvey and Steinhauer, 1974). Trichloro- and tetrachlorobiphenyls predominate in these atmospheric samples (Bidleman and Olney, 1974a). Significant PCB levels in arctic fauna in areas where the atmosphere is the only plausible input source also indicate significant atmospheric transport of the polychlorinated biphenyls (Risebrough and Berger, 1971; Bowes and Jonkel, in press; Walker, in press).

Polychlorinated biphenyls consist of many different kinds of molecules that differ in the number of chlorine atoms and their positions on the parent biphenyl molecule. Commercial mixtures differ by their average chlorine content: commonly used preparations contain an average of 42%, 48%, 54%, or 60% chlorine by weight, consisting predominantly of trichloro-, tetrachloro-, pentachloro-, and hexachlorobiphenyls, respectively. An account of their principal indus-

trial applications and probable routes of environmental input has been given by Nisbet and Sarofim (1972). Japan, the Soviet Union, Canada, and the United States are, or have been, major users of PCB. The PCB in Amchitka ecosystems might therefore derive, via atmospheric or oceanic transport, from all these countries as well as from countries more remote. The major portion of the PCB that has been used consists of mixtures in which trichlorobiphenyls predominate (Nisbet and Sarofim, 1972). The Japanese product with this chlorine composition is marketed under the name Kanechlor-300 (Kuratsune and Masuda, 1972); the corresponding American preparation is Aroclor 1242. Among environmental samples, birds and mammals usually contain PCB of a somewhat higher chlorine content, consisting of pentachloro- and hexachlorobiphenyls.

MATERIALS AND METHODS

Samples were collected on Amchitka Island in the course of field studies carried out from 1969 through 1974. The majority of the samples were frozen until analysis; several were preserved in Formalin in glass jars. Tissues were ground with anhydrous sodium sulfate. Lipids were soxhlet-extracted with hexane:acetone (2:1). Cleanup was accomplished with sulfuric acid:fuming sulfuric acid:celite columns (Stanley and LeFavoure, 1965; Risebrough et al., 1970).

Both nonpolar OV-1 and polar QF-1 columns were used in the gas chromatographic analyses. Since several of the principal PCB peaks as well as several of the chlorinated hydrocarbons of insecticide origin emerge at different times from the two columns, identity is partially confirmed. In addition, many samples were saponified to remove interference with PCB determination by two of the principal DDT compounds, *p,p'*-DDT and *p,p'*-DDD (Risebrough, Reich, and Olcott, 1969).

The predominant chlorobiphenyls in each sample were determined through comparison with standards of Aroclor 1242, 1248, 1254, and 1260. Polychlorinated biphenyl with profiles on the gas chromatograms most resembling that of Aroclor 1260 was quantified by averaging three determinations with the use of three of the most prominent peaks of Aroclor 1260. Similarly, PCB with a profile most resembling Aroclor 1254 was quantified by averaging three determinations based on the three principal peaks emerging after *p,p'*-DDE with the use of the OV-1 column.

A fishing float from the Japanese fleet, found on a beach on Amchitka, was soxhlet-extracted for

10 hr with 600 ml of hexane. The extract was found to have a gas chromatographic profile identical to either Aroclor 1248 or the equivalent Japanese preparation Kanechlor-400. The extract was quantified on the basis of one characteristic peak from the Aroclor 1248 standard. The PCB in samples containing predominantly trichlorobiphenyls was also quantified on the basis of one of the characteristic peaks.

The majority of the samples were analyzed at the Bodega Marine Laboratory with these methods. The remainder were analyzed by the Inter-Mountain Laboratory in Salt Lake City through the assistance of the Environmental Protection Agency and the Utah State Board of Health.

RESULTS AND DISCUSSION

Analytical results are given in Table 1. Selected data of DDE and PCB residue determinations in the same species or in closely related species that are biocoenetic equivalents from other areas of the Pacific basin or of the arctic are also included for purposes of comparison. To date comparatively few studies have been made of chlorinated hydrocarbon distributions in Pacific Ocean ecosystems. Sample sizes are therefore necessarily small. Nevertheless, sufficient data are now available to begin to put together a picture of the overall contamination patterns.

Peregrine Falcon (*Falco peregrinus*) tissue samples included four addled eggs and the liver, brain, and breast muscle of a fledgling killed by a Bald Eagle (*Haliaeetus leucocephalus*). These residue levels are compared with determinations of chlorinated hydrocarbons in eggs of peregrines from Amchitka by other investigators (Peakall et al., 1975), with DDE and PCB concentrations in two unhatched peregrine eggs from West Greenland (Walker, Mattox, and Risebrough 1973a), the yolk obtained from the oviduct of a female peregrine that died at Morro Rock, California, in 1969, the breast muscle of this bird (Risebrough, unpublished results), the carcass of an adult peregrine from coastal California obtained in 1966 (Risebrough et al., 1968), two samples of biopsy fat of peregrines from coastal Chile (Walker et al., 1973b), and an addled egg of a closely related species, the New Zealand Falcon (*Falco novaeseelandiae*), obtained on the Auckland Islands in subantarctic New Zealand in 1973 (Bennington et al., 1975). The latitude of the Auckland Islands in the southern hemisphere is the same as that of Amchitka in the northern hemisphere; samples from the two areas may therefore be used to compare contamination levels in the two hemi-

Table 1 Levels of PCB and DDE in Amchitka Habitat Systems; A Comparison with Biocoenetic Equivalents in the Pacific Basin

Food and habitat type	Locality	Species and date	Tissue	Lab.*	No.	Percent lipid	DDE, † ppm	PCB, † ppm		Dominant biphenyls	PCB/DDE	Ref. ‡
Raptor, primarily avian carnivore	Amchitka	Peregrine Falcon, 1970	Addled egg	B	1	19	11 D	160 D	870 L	Pentachloro-	14.9	(1)
			Addled egg	B	1	29	56 D	190 D	660 L	Pentachloro-	3.3	(1)
			Addled egg	B	1	13	20 D	66 D	510 L	Pentachloro-	3.2	(1)
		Peregrine Falcon, 1972	Addled egg	IML	1	ND	1.7 W	2.1 W	ND	Pentachloro-	1.2	(1)
		Peregrine Falcon, 1971, fledgling	Pectoral muscle	B	1	5.5	1.2 W	10.7 W	202 L	Pentachloro-	8.8	(1)
		killed by eagle	Brain	B	1	4.4	0.2 W	2.1 W	49 L	Pentachloro-	10.5	(1)
			Liver	B	1	2.3	0.3 W	3.4 W	146 L	Pentachloro-	10.8	(1)
		Peregrine Falcon, 1971	Egg		3		23 D	114 D		ND	5	(2)
		Peregrine Falcon, 1973	Egg		7		26 D	145 D		ND	6	(2)
	West Greenland	Peregrine, 1972	Addled egg		1	9.9	36 W	40 W	403 L	Hexachloro-	1.1	(3)
			Dead embryo		1	3.1	9 W	6.3 W	210 L	Hexachloro-	0.7	(3)
	California coast	Adult peregrine, 1969	Yolk—oviduct		1	19.3	93 W	55 W	280 L	Hexachloro-	0.6	(4)
			Breast muscle		1	5.6	39 W	20 W	350 L	Hexachloro-	0.5	(4)
	Chilean coast	Adult peregrine, 1972	Carcass		1	3.3	74 W	65 W	1980 L	ND	0.9	(5)
			Biopsy fat		1	46	60 L		150 L	Hexachloro-	2.5	(6)
	Auckland Islands, N.Z.		Biopsy fat		1	71	120 L		170 L	Hexachloro-	1.4	(6)
		New Zealand Falcon, 1973	Addled egg		1	5.6	3.8 W	4.9 W	88 L	Hexachloro-	1.3	(7)
Raptor, primarily avian carnivore, terrestrial	Amchitka	Gyrfalcon, 1970	Pectoral muscle	B	1	3.1	7.5 L	0.58 W	19.5 L	Hexachloro-	2.7	(1)
			Brain	B	1	6.1	0.8 L	0.13 W	2.1 L	Hexachloro-	2.7	(1)
	Seward Peninsula, Alaska	Gyrfalcon, 1970, 1971	Biopsy fat		10	100	22 L		34 L	Hexachloro-	2.8	(8)
Raptor, feeding on birds, mammals, and fish	Amchitka	Bald Eagle, 1971	Addled egg	B	1	100	32 L		80 L	Hexachloro-	2.5	(1)
			Addled egg	B	1	100	36 L		134 L	Hexachloro-	3.7	(1)
			Pectoral muscle subcutaneous fat	B	1	14	3.4 W	9.9 W	63 L	Hexachloro-	2.9	(1)
		Bald Eagle, 1972	Addled egg	IML	1	ND	1.9 W	2.9 W§	ND	ND	1.6	(1)
Mammalian	Agattu		Addled egg	IML	1	ND	4.3 W	3.5 W§	ND	ND	0.8	(1)
		Harbor seal, 1974	Back muscle	B	1	7.9	0.021 W	0.033 W	0.42 L	Tetrachloro-Hexachloro-		(1)
							(0.23 W, p,p'-DDT)	0.030 W	0.38 L			
		Steller's sea lion, 1974	Back muscle	B	1	22.3	0.24 W	0.47 W	2.1 L	Pentachloro-	2.0	(1)
Mammalian	Auckland Islands	Hooker's sea lion, 1972	Subcutaneous fat	B	1	100	0.42 L		0.083 L	Hexachloro-	0.20	(7)
	Agattu	Arctic fox, male, 1974	Leg muscle	B	1	6.5	0.03 W	1 W	20 L	Tetrachloro-, pentachloro-, hexachloro-	30	(1)
			Liver	B	1	9.7	<.2 W	2 W	20 L	Tetrachloro-, pentachloro-, hexachloro-	>10	(1)

(Table continues on page 618.)

Table 1—(Continued)

Food and habitat type	Locality	Species and date	Tissue	Lab.*	No.	Percent lipid	DDE,† ppm	PCB,† ppm		Dominant biphenyls	PCB/DDE	Ref.‡
Coastal herbivores and omnivores		Arctic fox, female, 1974	Leg muscle	B	1	10.0	<.02 W	2 W	20 L	Tetrachloro-, pentachloro-, hexachloro-	>100	(1)
			Liver	B	1	8.7	<.02 W	2 W	30 L	Tetrachloro-, pentachloro-, hexachloro-	>100	(1)
	Amchitka	Emperor Goose, 1971	Breast muscle, lipid	B	1	100	0.6 L		7.0 L	Pentachloro-	11	(1)
			Breast muscle	B	1	100	0.005 L		0.3 L	Pentachloro-	60	(1)
	Attu	Norway rat, 1970 or 1971	Whole body	IML	1	ND	0.01 W	0.22 W		ND	22	(1)
		Norway rat, 1974	Whole body	IML	1	ND	<0.01 W	0.23 W		ND	>23	(1)
			Whole body	B	2	3.7	<0.04 W	6.0 W	160 L	Pentachloro-, hexachloro-	>150	(1)
	Amchitka	Norway rat, 1974	Whole body	B	1	12.3	<0.01 W	3 W	24 L	Tetrachloro-, pentachloro-, hexachloro-	>300	(1)
Terrestrial	Amchitka	Rock Ptarmigan, 1970	Carcass homogenate	B	10	2.8	0.0006 W	0.005 W	0.19 L	Pentachloro-	8	(1)
			Carcass homogenate	B	10	2.9	0.0012 W	0.005 W	0.16 L	Pentachloro-	4	(1)
	Seward Peninsula	Willow Ptarmigan, 1970, 1971	Carcass homogenate		6	1.9	0.009 W	0.016 W	0.84 L	Pentachloro-	1.8	(8)
		Rock Ptarmigan, 1970, 1971	Carcass homogenate		6	2.0	0.0016 W	0.005 W	0.24 L	Pentachloro-	3	(8)
Coastal fish	Attu Island	Rock Ptarmigan, 1974	Carcass homogenate	B	1	2.5	0.0011 W	0.0039 W	0.14 L	Pentachloro-	4	(1)
	Amchitka	Rock Greenling, 1970	Body section	B	1	1.2	<0.0001 W	0.06 W	4.8 L	Trichloro-	8	(1)
			Whole-body homogenate: replicate 1	B	10	3.0	0.008 W	0.18 W	6.1 L	Pentachloro-	22	(1)
			Whole-body homogenate: replicate 2			2.8	(0.02, p,p'-DDT) 0.009 W	0.20 W	7.0 L	Pentachloro-	22	(1)
		1974 (Pacific Ocean side)	Whole-body homogenate	B	3	1.9	(0.021, p,p'-DDT) 0.002 W	0.02 W	1.2 L	Tetrachloro-	6	(1)
		1974 (Bering Sea side)	Whole-body homogenate	B	3	2.8	0.003 W	0.008 W	0.3 L	Tetrachloro-, pentachloro-	3	(1)
		Spotted snailfish, 1974	Whole-body homogenate	B	3	1.6	(0.002, p,p'-DDT) 0.0013 W	0.015 W	0.6 L	Pentachloro-	5	(1)
		Pacific cod, 1974	Whole-body homogenate	B	1	0.8	0.005 W	0.010 W	0.6 L	Trichloro-	8	(1)
							(0.002 W, p,p'-DDT) 0.0018 W	0.016 W	2.0 L	Pentachloro-	3	(1)
		Dolly Varden trout, 1974	Whole-body homogenate	B	3	2.1	0.0018 W	0.01 W	0.5 L	Trichloro-	5	(1)
		Smooth lumpsucker, 1974	Whole-body homogenate	B	1	1.4	0.0024 W	0.01 W	0.7 L	Pentachloro-	5	(1)
							(0.0025 W, p,p'-DDT) <0.1 D	0.004 W	0.3 L	Trichloro-	2	(1)
							0.008 W	0.6 L	Pentachloro-	4	(1)	
Fishing float	Amchitka beach		Whole float	B	1					Tetrachloro-		(1)

Fish eater	Amchitka	Red-faced Cormorant, 1971	Yolk	B	1	20	0.76 W	3.8 W	19 L	Hexachloro-	5.0	(1)
			Pectoral muscle	B	1	100	3.5 L		21 L	Hexachloro-	6	(1)
		Red-faced Cormorant, juvenile, 1974	Pectoral muscle	B	1	3.9	0.04 W	0.02 W	0.6 L	Tetrachloro-		(1)
								0.08 W	2 L	Hexachloro-		(1)
		Pelagic Cormorant, 1974	Pectoral muscle	B	1	4.0	0.03 W	0.3 W	8 L	Hexachloro-	10	(1)
	Agattu	Red-faced Cormorant, 1974	Pectoral muscle	B	1	3.8	0.09 W	0.2 W	4 L	Tetrachloro-	2	(1)
							0.4 W	10 L	Pentachloro-	4	(1)	
	Peru	Guanay, 1969	Egg lipid	B	4	100	12.2 L (geometric mean)		15 L (geometric mean)	ND	1.2	(9)
							0.9 L (geometric mean)		0.25 L (geometric mean)	Hexachloro-	0.3	(7)
	Auckland Islands	Auckland Island Shag	Egg lipid	B	4	100	754 L (arithmetic mean)		87 L (arithmetic mean)	Pentachloro-	0.1	(10)
Alcids and pelagic species	Southern California	Double-crested Cormorant, 1969	Egg lipid	B	7	100	574 L (arithmetic mean)		422 (arithmetic mean)	Pentachloro-	0.7	(10)
	Northwestern Mexico	Double-crested Cormorant, 1969–1970	Egg lipid	B	6	100						
	Amchitka	Pomarine Jaeger, 1971	Carcass	B	1	6.7	1.1 W	0.25 W	3.4 L	Pentachloro-	0.23	(1)
	Agattu	Black-legged Kittiwake, 1974	Whole body	B	1	7.6	0.07 W	0.15 W	2 L	Tetrachloro-		(1)
							0.6 W	7 L	Hexachloro-	10	(1)	
	Amchitka	Least Auklet, 1971	Whole body	B	1	6.9	0.03 W	0.13 W	1.9 L	Pentachloro-	5	(1)
		Parakeet Auklet, 1971	Whole body	IML	1	ND	0.02 W	0.4 W§		ND	20	(1)
			Whole body	IML	1	ND	0.01 W	0.3 W§		ND	30	(1)
		Parakeet Auklet, 1974	Carcass	B	1	4.5	0.07 W	0.1 W	3 L	Tetrachloro-	1	(1)
							0.1 W	3 L	Hexachloro-	1	(1)	
Migrants and Asiatic species	Agattu	Tufted Puffin, 1974	Pectoral muscle	B	1	3.5	0.07 W	0.25 W	7 L	Pentachloro-	4	(1)
		Thick-billed Murre, 1974	Carcass	B	1	4.0	0.08 W	0.09 W	2 L	Hexachloro-	1	(1)
	Snares Islands, N.Z.	New Zealand Diving Petrel, 1971	Whole body	B	3	10.6	0.009 W (geometric mean)	0.009 W	0.09 L	Pentachloro-	1	(7)
	Amchitka	Fulmar, 1970	Pectoral muscle	B	1	4.7	0.07 W	0.55 W	12 L	Hexachloro-	7	(1)
		Leach's Storm Petrel, 1970	Whole body	B	1	2.1	0.51 W	0.8 W	27 L	Hexachloro-	2	(1)
	Shemya Island	Spinetail Swift, 1974	Carcass	B	1	2.1	3.8 W	0.4 W	28 L	Pentachloro-	0.14	(1)
	Amchitka							0.03 W		Tetrachloro-		(1)
								0.04 W		Pentachloro-	0.25	(1)
		Bristle-thighed Curlew, 1974	Carcass	B	1	ND		0.004 W	0.06 L	Trichloro-		(1)
		Bean Goose, 1974	Pectoral muscle	B	1	6.6	<0.0001 W (0.0006 W, p,p'–DDT)	0.009 W	0.14 L	Pentachloro-		(1)
		Liver	B	1	6.0	0.0003 W	0.01 W	0.18 L	Trichloro-		(1)	
							0.003 W	0.08 L	Pentachloro-	10	(1)	

*B, Bodega Marine Laboratory; IML, Inter Mountain Laboratory.

†W, wet weight; D, dry weight; L, lipid weight.

‡References: (1) This paper; (2) Peakall et al., 1975; (3) Walker et al., 1973a; (4) Risebrough, unpublished; (5) Risebrough et al., 1968; (6) Walker et al., 1973b; (7) Bennington et al., 1975; (8) Walker, in press; (9) Risebrough, Anderson, and McGahan, unpublished; (10) Gress et al., 1973; ND, not determined.

§Quantitated with Aroclor 1254.

spheres. The PCB values in the three eggs obtained on Amchitka in 1970 and the eggs subsequently obtained in 1971 and 1973 are among the highest of the recorded values, exceeded only by the residues in the body fat of an adult female in California. The latter value may be considered elevated because of depletion of body-fat reserves during illness of the bird (Risebrough et al., 1968). Ratios of PCB to DDE were also higher in the Amchitka samples. A local source of the contaminating PCB is therefore suggested; alternatively, these high PCB values may reflect high past input of PCB into the marine environment from Japanese sources.

Within an ecosystem, peregrines and other species of bird-eating raptors accumulate the highest residues of organochlorine pollutants (Ratcliffe, 1970; Risebrough et al., 1968). On Amchitka high levels of the DDT compound p,p'-DDE have been recorded in the peregrines, and shells of peregrine eggs on Amchitka have become significantly thinner than the shells in museum collections obtained before 1946 (White, Emison, and Williamson, 1973; Cade et al., 1971). Peregrines and other bird-eating raptors are also the first species in an ecosystem to show reproductive failures and population declines associated with organochlorine contamination (Hickey, 1969; Ratcliffe, 1970; Cade et al., 1971). Table 1 shows that the peregrines have the highest concentrations of DDE and PCB of all the species examined on Amchitka.

Between April and July 1968-1972, 548 food items of peregrines were obtained on Amchitka (White et al., 1973). Seventy percent consisted of alcids; of them, 24% were Crested Auklets (*Aethia cristatella*), 15% were Ancient Murrelets (*Synthliboramphus antiquus*), and 23% were Least (*Aethia pusilla*), Whiskered (*Aethia pygmaea*), and Parakeet (*Cyclorhynchus psittacula*) Auklets. After mid-June falcons were seen more frequently on land than at sea. Prey items included the Green-winged Teal (*Anas crecca*), Lapland Longspur (*Calcarius lapponicus*), Gray-crowned Rosy Finch (*Leucosticte tephrocotis*), and Rock Ptarmigan (*Lagopus mutus*). Therefore during the breeding season the bulk of the peregrine prey was marine rather than terrestrial.

On a lipid basis (60 to 190 ppm lipid weight), DDE levels in the peregrine eggs from Amchitka are equivalent to the DDE levels in the fat, obtained by biopsy, of two adult peregrines examined in Chile in 1972. The addled egg of the New Zealand Falcon obtained in the Auckland Islands in 1973 contained 76 ppm DDE lipid basis. The DDE contamination at the latitude of the Auckland Islands appears therefore to be of the

same order of magnitude as contamination levels at equivalent latitudes in the northern Pacific. The PCB concentration, however, in the New Zealand Falcon egg was an order of magnitude lower than that in the Amchitka peregrine eggs.

Gyr Falcon (*Falco rusticolus*) are frequent on Amchitka but apparently do not breed there (White, Emison, and Williamson, 1971). Prey items recovered on Amchitka and observations of feeding behavior indicate that approximately 80% of the diet of the Gyr Falcon consists of ptarmigan; ducks, Snow Buntings (*Plectrophenax nivalis*), rosy finches, and longspurs constitute the remainder. The single individual analyzed contained lower residues than 10 adults of the Seward Peninsula in western Alaska from which biopsy fat samples were obtained in 1970 and 1971 (Table 1) (Walker, in press). Geometric mean values of residues in the Seward Peninsula birds were two to three times higher, but the range was large: 0.7 to 290 ppm DDE; 6 to 210 ppm PCB. The higher concentrations, however, are associated with those Gyr Falcons preying on summer migrants, which have much higher residue burdens than do the resident ptarmigan (Walker, in press). The lower concentrations in the single bird from Amchitka do not therefore necessarily suggest that contamination levels differ in these regions, being 2.7 and 2.8 in the Amchitka and Seward Peninsula birds, respectively.

Bird material constitutes the major food of Bald Eagles (*Haliaeetus leucocephalus*). Among 639 food items collected, 61% consisted of birds, principally gulls, auklets, cormorants, and assorted ducks. Mammals constituted 23% of the items, of which more than half were sea otters (*Enhydra lutris*). Fish and marine invertebrates constituted the remaining 16% (Sherrod, 1975). Because of water loss, PCB levels in two eagle eggs were analyzed on a lipid basis and found to be 80 and 134 ppm. The DDE levels were lower by approximately a factor of 3 (Table 1). Residue levels have previously been reported for Bald Eagles from the Admiralty Island area in southeastern Alaska and from Kodiak (Wiemeyer et al., 1972). One eagle egg from South Midway Island near Admiralty Island contained 11 ppm DDE and 2.3 ppm PCB wet weight. Residues in four other eggs from the area were much lower, averaging 0.95 ppm DDE and 0.75 ppm PCB. To the west on Kodiak Island, seven eggs averaged 1.9 ppm DDE and 2.2 ppm PCB. If the percent lipid in Bald Eagle eggs is assumed to be 5%, our PCB values from Amchitka, considerably to the west and more oceanic, are somewhat higher than those closer to the North American continent.

Samples of back muscle were provided from two pinnipeds, the harbor seal (*Phoca vitulina*) and the Steller's sea lion (*Eumetopias jubata*), both found dead at the beach at Agattu Island in the Aleutian chain in 1974. In the harbor seal PCB consisted predominantly of a mixture of tetrachloro- and hexachlorobiphenyls; both were present in quantities slightly higher than levels of p,p'-DDE. Pentachlorobiphenyls in the Steller's sea lion sample were approximately twice as concentrated as p,p'-DDE. In contrast, PCB levels were lower in subcutaneous fat of a Hooker's sea lion (*Otaria hookeri*) at an equivalent latitude in the southern hemisphere in 1972; DDE values, however, were intermediate between those in the harbor seal and those in the Steller's sea lion (Table 1; Bennington et al., 1975). This comparison between the contamination levels in the two hemispheres is therefore comparable to that made above between the peregrine and the New Zealand Falcon.

The Arctic fox (*Alopex lagopus*) is a beach scavenger; two specimens were obtained from Agattu Island. Concentrations of p,p'-DDE were low but comparable, however, to those of the harbor seal from the same island. The PCB consisted of a mixture of tetrachloro-, pentachloro-, and hexachlorobiphenyls; the profile was similar in the four tissues examined but differed from the gas chromatographic profiles of standard mixtures in that a number of the PCB compounds had selectively accumulated whereas others had been excreted or metabolized. These substantially higher PCB concentrations in the fox tissues than those in the harbor seal and sea lion suggest a source of PCB that is not available to the food webs that support the pinnipeds; flotsam and beach refuse from ships possibly contain substantial amounts of PCB. The foxes were collected from an area uninhabited since the 1950s.

This hypothesis is supported by the comparatively high PCB concentrations in Norway rats (*Rattus norvegicus*), which live primarily on the beach and which feed on rotten kelp and a variety of animal and vegetable material. Two rats obtained from Attu Island in 1974 contained a mean value of 160 ppm PCB lipid weight consisting of a mixture of pentachloro- and hexachlorobiphenyls. A rat obtained on Amchitka in 1974 had somewhat lower PCB concentrations; these were, however, an order of magnitude higher than those in two rats obtained on Amchitka in 1970 or 1971. The PCB : DDE ratios were exceptionally high in all samples, again suggesting beach sources of PCB contamination.

Emperor Geese (*Philacte canagica*) are primarily intertidal, feeding principally on beach

lettuce (*Ulva*), assorted grasses, and invertebrates. They spend about 6 months of the year on Amchitka. Two samples of breast muscle from birds obtained in 1971 were analyzed. Both contained predominantly pentachlorobiphenyls; PCB concentrations in the two samples differed by a factor of 20 lipid weight.

Two terrestrial plants [horsetail (*Equisetum arvense*) and crowberry (*Empetrum nigrum*)] are the principal foods of the Rock Ptarmigan (*Lagopus mutus*) and constitute in the order of 90% of the dry weight ingested (W. Emison, C. M. White, and F. S. L. Williamson, unpublished observations). The only plausible source of chlorinated hydrocarbons in tissues of these birds is atmospheric fallout onto land; ptarmigan are upland birds that do not generally approach the coast and therefore are not exposed to marine contamination. Twenty skinned carcasses of ptarmigan obtained in 1970 were divided into two portions and homogenates made of each. Residues were very low, on the order of 0.02 to 0.04 ppm DDE and 0.16 to 0.19 ppm PCB in the body lipids (Table 1). Residue levels and PCB : DDE ratios were very close to those found in a sample of six Rock Ptarmigan from the Seward Peninsula in western Alaska (Walker, in press). The level of atmospheric fallout in the two regions appears therefore to be comparable. The PCB in these Rock Ptarmigan and in Willow Ptarmigan (*Lagopus lagopus*) obtained on the Seward Peninsula in 1970 and 1971 consisted predominantly of pentachlorobiphenyls. A Rock Ptarmigan obtained on Attu Island in 1974 also contained pentachlorobiphenyls in the same ratio to DDE as those samples obtained earlier but contained, in addition, substantial quantities of trichlorobiphenyls at levels approximately twice those of the pentachlorobiphenyls (Table 1). The sample was collected within 4 miles of a Coast Guard Loran station.

In the fish examined DDE concentrations were relatively constant, ranging between 1 and 5 ppb, except those in the rock greenling (*Hexagrammos lagocephalus*), a fish inhabiting coastal inshore waters which was obtained in 1970. Replicates of a homogenate of 10 fish obtained in 1970 contained 8 and 9 ppb, respectively, of p,p'-DDE; the body section of a larger fish contained less than 0.1 ppb on a wet-weight basis (Table 1).

Fish of all species obtained in 1974 did not diverge widely in PCB concentrations; values ranged from 0.3 to 2.0 ppm lipid weight but showed considerable variation in PCB composition. On a lipid-weight basis, the rock greenling obtained in 1970 contained substantially higher PCB concentrations. The homogenates of the small rock greenling obtained in 1970 contained predomi-

nantly pentachlorobiphenyls, whereas the body sections of larger fish contained principally tetrachlorobiphenyls. Tetrachlorobiphenyls were also present in rock greenling obtained in 1974; fish from the Pacific Ocean side of the island contained approximately three times the concentrations of tetrachlorobiphenyls as fish from the Bering Sea side of the island. The latter, however, also contained p,p'-DDT and pentachlorobiphenyls.

Three spotted snailfish (*Liparis callyodon*), small intertidal fish that do not leave the intertidal zone, contained predominantly trichlorobiphenyls. A Pacific cod (*Gadus macrocephalus*) obtained at an eagle's nest on Amchitka Island contained a very different chlorinated biphenyl composition, consisting predominantly of pentachlorobiphenyls. The PCB : DDE ratio of approximately 3 was similar to that recorded in earlier samples of eggs of the Bald Eagle on Amchitka (Table 1). Dolly Varden (*Salvelinus malma*), an anadromous species obtained in Jones Lake on Amchitka Island, contained DDE concentrations equivalent to those in other species but a mixture of both pentachloro- and trichlorobiphenyls. A smooth lump sucker (*Aptocyclops ventricosus*) collected from an eagle's nest but an intertidal species like the greenling and snailfish contained a mixture of trichloro- and pentachlorobiphenyls.

All intertidal fish contained mixtures of trichloro- and tetrachlorobiphenyls with one or the other predominating. A fishing float found on an Amchitka beach contained trace quantities of tetrachlorobiphenyls equivalent to the American PCB preparation Aroclor 1248 and the Japanese preparation Kanechlor-400. We assume that the PCB was accumulated by the float from ambient water. The coastal zone and perhaps also the offshore waters are therefore contaminated with both trichloro- and tetrachlorobiphenyls. We assume also that the presence of p,p'-DDT in this area is an indication of atmospheric fallout; fish containing detectable quantities of p,p'-DDT also invariably contained pentachlorobiphenyls.

Tetrachlorobiphenyls were detected in pectoral muscle of Red-faced Cormorants (*Phalacrocorax urile*) from both Amchitka and Agattu. Thus some of the tetrachlorobiphenyls present in fish persist in this cormorant. Residues in the Red-faced Cormorant and in the pectoral muscle of a Pelagic Cormorant (*Phalacrocorax pelagicus*) are compared with those in the egg lipids of other species of cormorants from coastal California, northwestern Mexico, Peru, and the Auckland Islands. On Amchitka the Pacific sand lance (*Ammodytes hexapterus*) is most frequently found in the food regurgitated by the young. In the 1971 samples, PCB levels on a lipid basis were approximately 20

ppm, comparable to the 15 ppm recorded in eggs of the Guanay (*Phalacrocorax bougainvillii*) from central Peru (R. W. Risebrough, D. W. Anderson, and J. McGahan, unpublished observations). These levels are much lower than residues in eggs of the Double-crested Cormorants (*Phalacrocorax auritus*) of southern California and northwestern Mexico, where average PCB residues in 1969 were found to be 87 and 422 ppm, respectively (Gress et al., 1973). These higher residues derive from industrial discharges in the Los Angeles area (Schmidt et al., 1971; Young et al., in press). On the Auckland Islands, in 1973 PCB residues in egg lipids of the Auckland Island Shag (*Phalacrocorax campbelli*) averaged less than a part per million (Bennington et al., 1975). Thus PCB levels at the same latitude in the northern and southern hemispheres appear to differ by an order of magnitude, whereas DDE levels in these closely related species are comparable; these cormorant data complement those obtained from seals and sea lions and from falcons, as discussed previously.

Among the alcids and pelagic species, tetrachlorobiphenyls were detected in a Black-legged Kittiwake (*Rissa tridactyla*) from Agattu and a Parakeet Auklet from Amchitka. In the North Atlantic, kittiwake specimens analyzed have shown consistently PCB : DDE ratios that are higher than those in other marine birds examined (Bourne and Bogan, 1972). The ratio of 10, hexachlorobiphenyl : DDE, in the Agattu kittiwake is noticeably higher than the ratio found in the Thick-billed Murre (*Uria lomvia*), also obtained on Agattu Island in 1974, but is not different from ratios found in other species of the area. High PCB : DDE ratios were found in the two Parakeet Auklets obtained in 1971, but lower ratios were found in a Least Auklet obtained in that year and in a Parakeet Auklet and a Tufted Puffin (*Lunda cirrhata*) obtained in 1974. Least and Parakeet Auklets are primarily subsurface feeders on zooplankton, principally a euphausiid of the genus *Thysanoessa*, and mysids of the genera *Acanthomysis* and *Stilomysis*. In Table 1 residues in these birds are compared with those recorded in the Diving Petrel (*Pelecanoides urinatrix*) from the Snares Islands (Bennington et al., 1975). The DDE levels in the New Zealand Diving Petrel are comparable to those in the Least and Parakeet Auklets obtained in 1971; DDE residues in the Parakeet Auklet, the Thick-billed Murre, and the Tufted Puffin obtained in 1974 appear to be somewhat higher.

Among the pelagic species, the Pomarine Jaeger (*Stercorarius pomarinus*) had a PCB : DDE ratio of 0.23, a ratio characteristic of California coastal waters, where DDE concentrations are generally

higher than those of PCB (Risebrough et al., 1968). Most of the residue burden of this bird may therefore have been acquired during migration. Concentrations and ratios in the Fulmar (*Fulmarus glacialis*) and in the Leach's Storm Petrel (*Oceanodroma leucorhoa*) are comparable to those in other species of the area. The DDE levels in these species were substantially lower than those in Fulmars and petrels taken off California (Risebrough et al., 1968); the PCB level in the Fulmar (0.55 ppm wet weight) may be compared to the three values of 0.08, 0.34, and 6.5 ppm wet weight in whole bodies of Fulmars taken off California (Risebrough et al., 1968). Trichlorobiphenyls were detected in a Bean Goose (*Anser fabalis*), a vagrant from Asia, collected on Amchitka in 1974. The DDE levels were very low in tissues of this bird. In contrast, a Spinetail Swift (*Hirundapus caudacatus*) collected on Shemya Island in 1974 and the first North American record of the species (C. M. White, unpublished observation) had exceptionally high DDE (3.8 ppm wet weight) and comparatively low PCB. A Bristle-thighed Curlew (*Numenius tahitiensis*) collected in May 1974 on Amchitka was the first Aleutian record; this species migrates to islands of the South Pacific from its Alaskan breeding grounds. This bird contained comparatively low levels of both DDE and PCB with DDE predominating.

The wide divergence in PCB composition among the specimens examined provides at best an imperfect comparison of PCB levels; this is particularly true in the comparisons of samples that consist predominantly of trichlorobiphenyls with those containing principally hexachlorobiphenyls. Pentachloro- and hexachlorobiphenyls are present, however, in the commercial mixtures of Aroclor 1242 and 1248. Thus samples containing principally pentachloro- and hexachlorobiphenyls do not necessarily reflect environmental exposure to these PCB mixtures. Rather, compounds of higher water solubility that are more readily metabolized may have been selectively excreted (Lincer and Peakall, 1973).

SOURCES OF PCB CONTAMINATION

Present and Past Human Activities

In 1943 the U. S. military established a base on Amchitka for a staging area from which to launch attacks on Japanese-occupied Attu and Kiska to protect the North American coastline. Up to 15,000 troops were based on the island during World War II; the base was abandoned in 1951. In 1959 the Western Electric Company constructed a site for the White Alice communications network

in the interior of the island. In 1964 Amchitka began to be used as a site for underground nuclear tests by the United States. The average population between 1968 and 1972 was between 300 and 500, with up to 750 present at peak times. Some of these activities may be assumed to have contributed PCB to the local environment. Moreover, waste materials were frequently burned; injection into the atmosphere and fallout back onto the land was therefore possible.

Hundreds of kilograms of plastic objects wash up on the beaches of Amchitka each year. These include bottles, fishing nets, polyethylene sheets, ropes, and other assorted plastic objects used by the Soviet and Japanese fishing fleets (T. R. Merrell, personal communication). Refuse from ships may therefore be the source of PCB in the intertidal organisms and animals foraging along the beach.

Storm tracks based on data available from 1899 to 1954 lie in a southwest-northeast direction during all seasons of the year. Summer winds tend to blow from the southwest, and west-northwesterly winds are frequent in fall and winter; at other times there is no prevailing wind direction (Armstrong, 1971, and Chap. 4, this volume). Prevailing surface winds immediately southward of the Aleutian chain in the vicinity of Amchitka are westerly at all seasons of the year (U. S. Weather Bureau and U.S. Hydrographic Office records).

The pattern of surface currents is considerably more complex. To the south the current carries water eastward to enter the Alaskan gyre. Near Amchitka surface currents are to the west, bringing, in part, water from the Alaskan gyre to the east (McAlister and Favorite, Fig. 1, Chap. 16, this volume).

Among polar ecosystems, organochlorine contamination of food webs has been studied on the Seward Peninsula in western Alaska (W. Walker, in press) and on the Antarctic Peninsula (Risebrough and Carmignani, 1972). The highest concentrations are found either in birds migrating into the area or in species that prey on them. Most of the species examined on Amchitka, however, are dependent on the local marine ecosystem, and the proportion of migratory birds is relatively small.

Airborne PCB from Japan can be expected to show the same exponential decrease with distance from its source as does PCB originating in the eastern United States and deposited in the North Atlantic (Harvey and Steinhauer, 1974). These residues are most likely carried farther east by the prevailing currents. Bidleman and Olney (1974a) have reported that PCB in atmospheric samples obtained over the North Atlantic consisted pre-

dominantly of trichloro- and tetrachlorobiphenyls; in seawater, however, pentachlorobiphenyls predominated, suggesting that the lower chlorinated compounds had been degraded, perhaps by ultraviolet light or by metabolism. These observations are inconsistent with the hypothesis that the trichloro- and tetrachlorobiphenyls found in the vicinity of Amchitka had traveled by atmospheric or ocean currents from Japan. Local sources of contamination, including the disposal of PCB-containing refuse on beaches, appear more plausible.

Sublethal effects of PCB that might be expected to impair reproductive capacity of birds have been reviewed by Vos (1972) and Peakall (1975). The species most vulnerable to organochlorine contamination on Amchitka is clearly the Peregrine Falcon. The DDE residues in this population are associated with some thinning of eggshells (White et al., 1973; Cade et al., 1971). Available data indicate that the present residue burdens are not impairing the reproductive capacity of this species, but increases in levels of either PCB or DDE could be expected to have deleterious effects. Fortunately the high levels of PCB in many ecosystems have prompted restrictions on PCB use on an international level; this should decrease the environmental input of these pollutants (World Health Organization, 1973).

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Ecological Consequences of Nuclear Testing

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Amchitka Island has a history of disturbance by modern man, including U.S. military operations on the island during World War II, antedating the underground nuclear tests Milrow and Cannikin, for which preparation began in 1966. Many of the terrestrial disturbances resulting from nuclear testing were superimposed on scars remaining from the military occupation.

Construction, road improvement, and the Milrow and Cannikin nuclear detonations resulted in the loss or deterioration of about 420 ha (1040 acres) of terrestrial habitat, or less than 1.5% of the total area of Amchitka. A few streams and lakes were polluted by drilling effluents or human wastes; normal flushing action is expected to restore the quality of most of these freshwater habitats. Irreversible effects in freshwaters include the drainage of several ponds, gross channel alteration in a part of one stream, and the creation of a new lake which is deeper and which has a greater volume than any of the more than 2100 natural lakes on the southeast half of Amchitka. About 6 ha (15 acres) of intertidal bench was displaced to a level above

the intertidal zone, and an undetermined amount of similar habitat was altered to some degree by lesser vertical displacement.

No type of habitat on the island was destroyed, and localized habitat losses in the terrestrial, freshwater, and marine ecosystems are believed to have been too slight to have permanent effects on associated biotic populations. No plant or animal population on or around the island was lost or endangered as a result of the tests, although substantial numbers of sea otters and freshwater and marine fish were killed by the Cannikin detonation. Posttest investigations show that the affected populations generally recuperated promptly through reproduction or recruitment from neighboring stocks.

The most significant ecologic consequence of the nuclear test program is believed to have been the adverse effects of scattered terrain disturbances on the aesthetic quality of the Amchitka landscape, an effect which was severe in localized areas and which will persist for decades or centuries.

This chapter summarizes what is now known about the impacts of nuclear tests on Amchitka ecosystems, and the ecological significance of those impacts is discussed. The prompt bioenvironmental effects of the two high-yield nuclear detonations, Milrow in 1969 and Cannikin in 1971, are described in Kirkwood (1970) and Kirkwood and Fuller (1972), respectively. Biological and physical effects of these tests are also described in Merritt (1970; 1973), U. S. Geological Survey (1970; 1972), and Gonzalez, Wollitz, and Brethauer (1974). Since those references do not discuss effects stemming from occupation of Amchitka by a sizable work force or the impact of support operations, such effects as well as those resulting directly from the nuclear detonations will be dealt with in this chapter.

Before we describe the overall impacts of the nuclear test program and assess their ecological consequences, we must review the more important

influences of modern man on Amchitka prior to the start of the recent AEC test series. It is only against this background that we can clearly identify and evaluate the additional impacts assignable to the nuclear test program for which preparations started in 1966 and which culminated in the Milrow and Cannikin tests.

BACKGROUND: PREVIOUS DISTURBANCES

Pre-World War II

The long and unsavory history of sea otter‡ hunting in the western Aleutians, first by the Russians and later by the Americans, is discussed in Chaps. 6 and 20 of this volume and elsewhere (e.g., Lensink, 1962). For our purposes it is sufficient to recall that fur hunting had nearly exterminated sea otters in the Aleutians, including Amchitka, before

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‡With two exceptions common names are used for plants and animals referred to in this chapter. Latin names for all other species mentioned will be found in the preceding chapters.

the species was placed under protection by the terms of an international treaty in 1911. Remnant populations remained on some islands. Kenyon (1969) estimates that as many as 100 sea otters may have remained at Amchitka when the protective treaty took effect. Under protection, sea otter populations at Amchitka and many other Aleutian Islands gradually recovered from the effects of overexploitation.

In 1921, under a fox-farming agreement between the U. S. Department of Agriculture and Aleuts living on Atka, blue foxes were introduced onto Amchitka (Merritt, Chap. 6, this volume). This deliberate introduction of a new predator had a predictable adverse effect on at least one avian species, the Aleutian Canada Goose, which formerly nested on Amchitka.*

Robert Jones, Jr., former Manager of the Aleutian Islands National Wildlife Refuge, of which Amchitka is a part, commented as follows on the effects of the fox-farming enterprise at Amchitka: "An episode in the island's history that can only be regarded, from the viewpoint of the utilization of lands devoted to wildlife purposes, as unwise and unfortunate, began according to our records, in 1921. It was in this year that seven blue foxes were placed on Amchitka by the native Atka residents as 'lessee' of the island for fox farming purposes. . . . We have the statement of the Atka natives that Canada geese were abundant nesters on Amchitka prior to 1921 and they attributed the disappearance of the population directly to the introduction of the foxes" (Jones, 1961).

The Aleutian Canada Goose still does not breed on Amchitka, although the fox population has been extirpated. The effects, if any, of foxes on the breeding success of other avian species is hard to evaluate since another predator, the Norway rat, was inadvertently introduced during World War II (Brechtbill, Chap. 12, this volume).

World War II Military Occupation

Many of the surface disturbances on Amchitka associated with AEC site preparation and operations are superimposed on the extensive areas of disturbance that date from occupation of the island by U. S. military forces. That occupation, over the period 1943 to 1950, produced widespread and persistent changes in the appearance of the island and had some important impacts on

island ecosystems. A complete inventory and description of changes wrought by military occupation is beyond the scope of this chapter, but some of the more obvious features must be called out as disturbances that predate nuclear tests on Amchitka.

Roads and Airstrips. Roads built by the military forces include a central roadway running almost the length of the island, a complex of roads around Constantine Harbor and extending across the island, and a number of branch roads running from the central roadway to either seacoast. Most roads were of dirt or dirt with gravel surfacing. (The Geological Survey map in the pocket at the back of this volume shows most of the important military roads.)

Three airstrips were constructed inland from Constantine Harbor. The longest, Baker Runway, is about 3 km (2 miles) long and is in use today. The airstrips are hard-surfaced, and the two longer ones are adjoined by numerous hardstands connected to the landing strips by taxiways.

Off-Road Traffic. Beyond the established roadways, military occupation left many scars on the tundra mantle, the result of single or multiple passes with tracked off-road vehicles. In the lowland part of the island, even regularly used footpaths remained as visible marks on the tundra.

Housing. Military housing consisted of nearly 1900 widely dispersed Quonset-type huts, mostly located near main or branch roads, primarily in the southeastern part of the island (Figs. 7 and 8, Chap. 6, this volume). In the construction of the huts, tundra vegetation and underlying peat was scraped aside and used to bank around the base of the building walls. Most buildings were framed of wood with masonite-type roofing and were left standing when the occupation ended. They are gradually disintegrating by weathering. Some have been burned by Refuge personnel, and others were burned by AEC contractors at the request of U. S. Department of the Interior representatives.

Other Construction. A dock was built on wood pilings on the north side of Constantine Harbor; lookout posts and gun emplacements were built at some points on the coastal bluffs. Two large gravel pits and a number of smaller quarries and borrow pits were opened to provide materials for road building and other construction.

Status at Termination of Military Occupation. When military occupation ended some salvageable material was removed, but most of the dispersed housing units and a considerable amount of debris were left in place. The disintegrating buildings are still a prominent feature of the

*A third of a century earlier, Turner (1886) had reported: "On some of these islands foxes of various kinds are numerous, hence while they are excellent feeding grounds for the geese in the fall, the geese are compelled to rear their young on the nearest islets where the foxes cannot molest the young goslings."

Amchitka landscape. Even where the buildings have been destroyed (by the elements or by fire), the peat embankments with which the bases of the hut walls were banked still mark the sites where they formerly stood. Exposed hut floors tend to remain waterlogged, and natural revegetation on the floors is occurring only very slowly.

Gravel pits and borrow areas were left pretty much as they were when quarrying stopped. Some were used as dumps for waste material, often without backfilling. Elsewhere debris was simply left on the surface of the tundra.

Some measure of the extent of disturbance to Amchitka resulting from World War II activities can be inferred from the "Draft Environmental Statement, Proposed Aleutian Islands Wilderness, Aleutian Islands National Wildlife Refuge, Alaska" (U. S. Bureau of Sport Fisheries and Wildlife, 1974). This report recommends that certain lands within the Refuge be excluded from the proposed Aleutian Islands Wilderness for various reasons. Among the types of lands proposed for such exclusion are those which "... contain major World War II or postwar installations, since abandoned." It is noteworthy that for Amchitka this is the basis cited for exclusion of 20,900 acres (8500 ha), or about 29% of the total area of the island. This is not to suggest that the entire area so designated is uniformly disturbed. It does mean that the various military remains, including roadways, airstrips, and other examples of disturbance, are so prominent an aspect of the landscape as to render it unsuitable for inclusion in a wilderness area. Figure 1 shows a portion of the island where World War II disturbance was most intensive. The nuclear tests took place within the area shown in Fig. 1.

Ecological Consequences. The terrain disturbances and landscape modifications caused by the military occupation are still evident today. Their adverse impact on the aesthetic quality of the Amchitka landscape is severe and will last for many decades. Other significant ecological consequences of the occupation are more difficult to identify but some can be recognized.

From an ecological point of view, the most important impact probably was the inadvertent introduction of the Norway rat. From Constantine Harbor, where they were first seen, rats gradually dispersed over the island. Kenyon (1961) observed: "Even today, nearly 10 years after the departure of the military, great colonies of rats persist in abandoned garbage dumps. From these centers of abundance they have spread to all parts of the island." The effects of rats on Amchitka bird populations are hard to assess, given the fact that

the blue fox, another nonnative predator, had earlier been established on the island through deliberate human intervention. Kenyon believed that rats had extirpated two nesting species, the Song Sparrow and the Winter Wren. However, some nesting areas must have escaped rat predation because recent studies show that breeding populations of the Winter Wren now exist on the island, and the Song Sparrow occurs on offshore islets where rats have not been seen (White, Williamson, and Emison, Chap. 11, this volume).

At least two species of nonnative plants were introduced during military occupation. Sweet clover is still found in scattered patches in the lowland part of the island. This perennial is not spreading because the plants apparently do not produce seed on Amchitka, perhaps because the insects required for pollination are lacking (Kazmaier, 1968). A few small Sitka spruce trees that were planted in front of military buildings still survive, although their growth in height has been minimal. Introduction of these nonnative plants is not known to have had any effect on Amchitka ecosystems.

There is some reason to speculate that military personnel, in an effort to improve sport fishing, may have stocked some landlocked ponds with Dolly Varden that had been caught in ponds and streams having access to the sea. This could explain the reported presence of the anadromous form of Dolly Varden in landlocked ponds (Valdez, Helm, and Neuhold, Chap. 14, this volume). If any genetic differences existed between the anadromous and landlocked forms, such transplanting could have obscured these differences in ponds where stocking occurred.

Finally, two habitat changes attributable to military occupation which may not have been entirely adverse were noted by avian ecologists participating in the bioenvironmental program. Roadside berms and tundra embankments around World War II housing units have come to support a dense stand of coarse native grasses, probably because of improved drainage. These grasses provide a good nesting habitat for Lapland Longspurs, Mallards, and Rock Ptarmigan (Williamson and White, 1974). In effect, this would seem to suggest that new breeding habitat for these species was created, although there is no way to determine whether the sizes of the breeding populations have been increased. Abandoned military buildings are also now commonly used as nesting places by Grey-crowned Rosy Finches. Williamson and Emison (1969) report that before World War II "... the breeding population was probably restricted to the coastal sea cliffs" However, in 1968 no nests were found on the cliffs, whereas many were found in deserted huts and other

Fig. 1—Map of a portion of Amchitka Island showing terrain disturbances resulting from military occupation of the island during World War II. Valid as of Mar. 17, 1948. (Adapted from Everett and Amundsen, 1975, Plate 1.)

World War II buildings. Thus the military occupation can be said to have created new nesting habitat for this species.

Post-World War II

Fish and Wildlife Service Management. When the military occupation of Amchitka ended in 1950, the U. S. Fish and Wildlife Service (FWS) resumed control of the island. In the early 1950s major management objectives of the Refuge staff were eradication of blue foxes and feral cats and dogs and reduction in the Norway rat population to foster use of Amchitka as a bird nesting habitat. Starting in 1950 and continuing through 1957, Robert D. Jones, Jr., then Refuge Manager, carried out an intensive predator poisoning campaign with strychnine and 1080* baits. The fox population dropped sharply from the start, and foxes are believed to have been extirpated by about 1960 (Kenyon, 1961). The rat population was also reduced in local areas where poisoning was concentrated, but rats were never entirely eliminated.

The predator eradication program had some adverse effects on carrion feeders, notably on the Bald Eagle and the Common Raven. Of the Bald Eagle, Kenyon (1961) states: "During the period of intensive fox poisoning at Amchitka, in the early and mid-1950's, the eagle population was somewhat reduced. Several dead birds were found that had eaten poisoned pellets. Local reproduction and an influx of birds from other areas, however, quickly restored the population, and in 1959, it had apparently again reached its natural ceiling." Kenyon also notes: "The raven was formerly resident on Amchitka (Jones, *in litt*). The fox poisoning program has, however, now eliminated the resident population, but occasional pairs visit the island." White et al. (personal communication) considered the ravens seen on Amchitka during the recent bioenvironmental studies to be visitants from nearby islands where they still breed, which suggests that the status of this species on the island has been altered in a persistent way by the use of poisons to eradicate foxes.

Between 1951 and 1959, FWS personnel carried out natural-history studies at Amchitka, the effort being focused mainly on the sea otter. Otters were captured and held in captivity for extended periods for physiological investigations, and several attempts were made to transplant small groups of otters to other locations. According to Abegglen (Chap. 20, this volume), 180 otters were removed from Amchitka during the 1950s. Given the existence of a large sea otter population distributed around the entire island and "overexploiting its

habitat" (Kenyon, 1969), there is no reason to believe that the removal of this number of animals for study or transplant attempts had any adverse ecological consequences.

White Alice Station: 1959–1961. Western Electric Company crews were on Amchitka from 1959 to 1961 constructing and operating a relay station of the "White Alice" communications system, part of the Distant Early Warning network (DEW Line). The station was located adjacent to Infantry Road, about 1.5 km northwest of the Cannikin test site. Several acres of theretofore undisturbed tundra were stripped of vegetation in building the installation. The accumulated litter and debris associated with building and occupation of the site were left on the surface when the station was closed down.

The loss of a few acres of terrestrial habitat as a result of this disturbance had only a trivial impact on the terrestrial ecosystem, particularly when viewed against the massive disturbances attributable to the earlier military occupation. However, the scar left in the landscape represents a further deterioration of the aesthetic values of the island, values that must be considered an important feature of the Refuge lands.

Sea Otter Harvests and Transplants: 1962 Through 1971. Starting in 1962 and continuing through 1971, substantial numbers of animals were deliberately removed from the Amchitka sea otter population. In 1962 and 1963 the Alaska Department of Fish and Game (ADF&G) harvested otters at Amchitka to secure skins for study and sale. The ADF&G made further harvests in 1967, 1970, and 1971. Also, during the 4-year period from 1968 through 1971, with cooperation from the AEC and the U. S. Fish and Wildlife Service, the ADF&G periodically captured sea otters at the island, transported them to distant locations in the United States and Canada, and released them in habitats where it was believed they would survive and reproduce. A few otters were also sacrificed in 1969 in experiments designed to determine their response to underwater pressure pulses. An account of the numbers of sea otters removed from Amchitka in the various harvest and transplant operations is given by Abegglen (Chap. 20, this volume). Chapter 20 also gives counts made of the island sea otter population starting in 1935 and continuing intermittently through 1974.

Between 1962 and 1971 some 1800 sea otters were taken from Amchitka for skins, for study purposes, and in transplant efforts. Nearly 1200 animals were removed during the period 1968 through 1971, when aerial population counts were being made annually with helicopter support.

*Sodium fluoroacetate, a widely used rodenticide.

The counts (see Chap. 20, Table 1) show no obvious population decline over the period of intensive removals. Since visual sea otter counts are imprecise (Estes, Chap. 21, this volume), the count data do not demonstrate conclusively that the removals had no impact on the Amchitka otter population. They do show that any impact they may have had was not great enough to be reflected in the population counts made over the period when the number of animals being taken was greatest.

Project Long Shot. In 1965 Amchitka was the site of an underground nuclear test, Long Shot, carried out by the Department of Defense with the assistance of the AEC. This test, and especially the associated operational activities, had some impact on the Amchitka landscape and ecosystems, although a minor one compared to that of the earlier military occupation.

Preparations for Long Shot began in 1964 with the drilling of several exploratory holes to check geological structure. An emplacement hole was later drilled at a site adjacent to Infantry Road, about 8 km (5 miles) northwest of the head of Constantine Harbor. The underground nuclear test of 80 kt explosive yield was carried out in October, 1965 at a depth of 2300 ft (700 m). Bioenvironmental effects of the detonation are discussed in Seymour and Nakatani (1967). Results of test-time observations and live-box experiments led to the conclusion that no biotic populations on or around the island were adversely affected by the explosion. The Long Shot bioenvironmental studies did not address the matter of effects due to human occupation, site preparation, and related operations.

Some local terrain disturbance and habitat destruction resulted from grading and leveling at and around the emplacement drill site. The cover of living vegetation as well as the underlying peat mantle was graded off an area of about 3 ha (7 acres) and pushed up in ridges around the site. Spoil and drilling wastes that could not be disposed of in this way were hauled away and dumped onto the tundra in several areas near the drill site. According to a scientist who participated in the Long Shot bioenvironmental studies, several miles of control and instrument cable was left on the tundra, and extensive use of off-road tracked vehicles left visible scars on the landscape within a radius of about 3 km (2 miles) around the emplacement site (Karl W. Kenyon, personal communication). These terrain disturbances, although very small in area compared to those of World War II, are unsightly and will remain visible for many years.

Terrain effects of the Long Shot underground nuclear explosion are described in considerable detail by Shacklette, Erdman, and Keith (1970). Effects observed included "... rupture of the tundra mat, damaged moss mounds, ... and slumping of earth banks." Disturbances of these types were scattered and mainly within a radius of 4000 ft (1200 m) from SZ,* although some ground slumping was observed on unstable coastal banks more than a mile from SZ. Damage to moss mounds consisted of splitting and cracking or ejection of blocks of tundra from the summits. Slumping of earth banks around ponds and along streams occurred in the vicinity of SZ and as far away as the Bering Sea coast. Water levels dropped in two ponds near SZ, and oil contamination (from drilling operations) was found in a stream draining the site area. Ground motion from the detonation is believed to have ruptured banks of settling basins, releasing the contaminants to the drainage. Localized and temporary flooding of small areas near SZ resulted in the death of lichens in the plant community, but other plants were apparently unaffected.

Some time after the Long Shot detonation, water in mud pits adjacent to the drill site was found to be contaminated with a low level of tritium. A peak level of 5130 tritium units (TU) was measured in surface-water samples collected near Long Shot SZ in 1966. Average values measured have been on the order of 1800 TU or less. The tritium levels in the Long Shot ponds remain higher than those in freshwaters elsewhere on the island but not high enough to constitute a hazard to man or to native biota (Seymour and Nelson, Chap. 24, this volume).

In summary, site preparation for the Long Shot test increased by several hectares the amount of disturbed terrain on the island and decreased the area of natural terrestrial habitat by a like amount.† Terrain disturbances caused by the detonation, some of which were detectable nearly 2 years after the test, are believed to be too scattered and too limited in extent to have any demonstrable adverse ecological consequences either in terms of reduced productivity or of permanent damage to the habitat. The detonation-

*SZ (surface zero) is the point on the surface directly above the point of the detonation.

†As part of the AEC demobilization and restoration effort after Milrow and Cannikin, the Long Shot site was cleared of surface debris, including the metal building left in place after the test. The SZ area was graded and seeded to grass (Nevada Operations Office, 1974).

related disturbances will gradually disappear under the influence of natural processes (weathering and growth of native vegetation).

IMPACTS OF AEC CONSTRUCTION, SITE PREPARATION, AND OCCUPATION

The first inventory of nondetonation effects of the 1966 to 1973 test program on Amchitka is that of Sowl* (1969a). This initial inventory was made in mid-1969, a few months before the Milrow test, and hence does not cover the impact of any operational activities that took place between Milrow and the completion of the AEC roll-up on the island in September 1973. Revised estimates of the extent of some terrain disturbances are given in Sowl (1969b). Neither reference addresses the question of effects caused by the nuclear explosions, but they are useful estimates of disturbances other than those related to the detonations since they were made after a large proportion of operational impacts had occurred. Everett and Amundsen (1975) also give an overall assessment of terrestrial impacts of the AEC test program on Amchitka but in more general terms than the inventories of Sowl (1969a; 1969b).

Road Improvement and Construction

To a large extent, road construction during the nuclear test program consisted of improvements to roads built during World War II, i.e., widening, regrading, and resurfacing of existing roadways. Wherever this was done, of course, any vegetation that had invaded the old roadways was destroyed. A few short sections of new roads were built, giving access to drill sites, instrument installations, and study areas. The longest new segment is a branch road about 2 km (1.2 miles) long extending northward from Rifle Range Point and built to provide access to an instrument site and study area at the head of Duck Cove, on the Pacific Ocean coast.

Sowl (1969a) estimated that improvements to Infantry Road plus the small amount of new road construction resulted in terrain disturbances totaling about 171 ha (422 acres). New road construction totaling at most a few hectares took place after Sowl's inventory. Road improvement and construction also required sand and gravel, which were obtained either by reopening World War II pits and borrow areas or by opening new ones.

(Gravel was used for other construction and for stemming emplacement holes, but much of it went into roads; all effects of quarrying are discussed under road construction.) Sowl (1969a) estimated that about 91 ha (225 acres) of terrain disturbance was ascribable to quarries, borrow pits, and associated spoil-disposal areas. Thus about 262 ha (647 acres) of terrestrial habitat was substantially disturbed by road improvement and construction; most of this disturbance was superimposed on the preexisting road system laid out during World War II.

This habitat disturbance or destruction, affecting less than 1% of the island surface, cannot be considered to have had any significant direct effect on Amchitka ecosystems. Locally, aesthetic values were adversely affected, e.g., where spoil was piled on previously undisturbed tundra or where new borrow areas were used along the roadway.

From an ecological viewpoint, the more important effects of road construction were indirect. Quarrying, road improvement, and new road construction resulted in siltation of a number of ponds and streams, an effect that had important, though probably short-term, adverse effects in the freshwater ecosystem. Almost all streams crossed by new or improved roads experienced some siltation, as did some ponds downstream from road crossings. Gravel quarrying and washing operations also produced stream and pond siltation, notably in the Silver Salmon drainage below Galion Pit. In Bridge Creek a considerable amount of siltation resulted from road improvement and channel alteration near the road. Pink salmon spawning in these drainages may have been affected by the silt deposition in spawning gravels. As of fall 1975, no spawning pink salmon had been observed in the Silver Salmon drainage since 1970, when the spawning run was estimated at 30 adults. In Bridge Creek four adults were seen in 1974 and none in 1975, compared to 15 in 1970 (Nelson, 1975).

In salmon surveys conducted in years subsequent to 1970, fewer spawning pink salmon have been seen in almost all streams, although some of the streams are sufficiently remote from AEC test sites to have escaped any influence of nuclear test activities. Of 21 streams in which pink salmon were observed to be spawning in 1970, 13 streams are known to have had spawners in 1974 and 4 in 1975 (the off year for this biennial spawner).†

*LeRoy Sowl was one of the wildlife biologists assigned by the U. S. Department of the Interior to monitor AEC activities on Amchitka and to advise on measures and practices to minimize adverse effects.

†Pink salmon runs in Amchitka streams are consistently larger in even-numbered years than in odd-numbered years (Valdez et al., Chap. 14, this volume). This is also true for Siberian streams but contrasts with those of the Puget Sound region, where pink salmon runs are heaviest in odd-numbered years (Burner, 1964).

Other Construction

Miscellaneous construction required to establish camps, laboratories, communication stations, and fuel-storage and other necessary support facilities is estimated to have disturbed or destroyed about 64 ha (158 acres) of terrestrial habitat. The areas affected range from about 12 ha (30 acres) down to 0.4 ha (1 acre) and are widely scattered throughout the island, generally along the roadways and often on the sites of World War II disturbances. Most of them represent sites where tundra and topsoil had to be graded off to permit the erection of a building or some other type of structure.

Site Preparation and Drilling

In all, eight potential nuclear test sites were considered during the AEC program. Of these, only two (Sites B and C) were actually used for tests. Large-diameter emplacement holes were also drilled at Sites D and F but were not used. An exploratory hole was drilled at Site E, whereas Site H was only graded preparatory to drilling. Sites A and G were located and staked, but no further preparation was made. Sowl (1969b) estimated that, at Sites B, C, D, E, F, and H, about 79 ha (195 acres) was disturbed by drilling or preparation for drilling. This figure includes access roads and spoil-disposal areas.

The most adverse effect associated with drilling operations was the release of noxious drilling fluids and particulate wastes into the freshwaters of the island. The spongy, porous nature of much of the tundra soils made containment of drilling fluids difficult, and precautions taken to maintain the integrity of drilling-sump walls were not always adequate. Spills occurred at all sites where drilling was carried on (Sites B, C, D, E, and F). At Site D the major spill occurred after drilling was suspended; ground motion from Cannikin breached a dike around a holding pond, allowing some 4800 m³ (30,000 barrels) of water and mud to flow into Falls Creek, which drains the site. The prompt biological consequences of this spill and a subsequent intentional release into the same drainage are described in Valdez et al., Chap. 14, this volume.

In a few instances small freshwater ponds were used for drilling-mud storage or waste disposal as an alternative to constructing holding ponds. Estimates made by Sowl (1969a), supplemented by knowledge of spills occurring after his inventory was made, indicate that freshwater contamination associated with drilling affected about 22 ha (55 acres) of ponds and 15 km (9 miles) of streams in seven drainages. The extent and persistence of the contamination varied.

A mud slide at Site E in 1968 resulted in substantial and persistent damage to the stream valley. Sumps were constructed on what proved to be unstable soil, which gave way under the weight of the liquid contents, causing a massive slide of semiliquid soil down the stream bed. As a result of this slide, the upper two-thirds of the stream course, about 1300 m (4300 ft) long, was grossly altered. Streamside vegetation was killed or severely damaged by the smothering effect of the muddy residue. This allowed the stream to deepen and widen its channel so that it no longer resembles the narrow grass-overhung lower part of the stream, which was little affected by the slide. The gross morphological changes in the upper stream course will persist for a very long time since much of the peat substrate that formerly maintained the integrity of the stream channel has eroded away (R. G. F., personal observation, 1975).

In those instances where contamination was limited to sporadic releases of drilling wastes or supernatant from drilling sumps, stream morphology was not altered; effects were primarily on populations of fish and invertebrates and changes in habitat, such as siltation of spawning gravels. The effects were largely transient in nature; toxic contaminants and silt were flushed from the streams during heavy flows, and fish and invertebrate populations had an opportunity to recover. Valdez et al. (Chap. 14, this volume) describe the results of a series of drilling-waste spills into Clevenger Creek from Site B (Milrow). In 1968 and 1969 toxic releases into the stream almost eliminated fish (juvenile Dolly Varden) and macroinvertebrates from the affected section of the Clevenger Creek drainage. Recovery of fish and invertebrates was nearly complete by 1974.

Studies of mud-spill effects and subsequent recovery of freshwater biota in other drainages contaminated by drilling operations were not as detailed as those in Clevenger Creek. There is good reason, however, to believe that restoration of normal habitat and biotic populations will ultimately take place in all drainages except that below Site E, where irreversible morphological changes in the stream occurred. In all instances where stream biota were adversely affected, parts of the drainages escaped contamination; stocks of fish and invertebrates remained available for recruitment to the affected portion once stream flushing had made the habitat suitable for recolonization.

Off-Road Vehicle Traffic

Tracked vehicles were used to some extent in several kinds of operations: cable laying, installa-

tion of monitoring stations, and travel to remote study sites. Some damage to the terrestrial habitat inevitably resulted from these off-road excursions; the amount and importance of this damage are difficult to assess. As recently as the summer of 1975, tracks made by a Snow-Trac that was used repeatedly* to travel from Infantry Road to the mouth of Midden Creek in 1970, 1971, and 1972 were still readily discernible; the vegetative cover is shorter and less diverse than that of the surrounding undisturbed tundra (R. G. F., personal observation). However, the tracks are fully vegetated except in a few swampy sections, and there is no reason to believe that this instance of off-road traffic significantly altered the terrestrial habitat. Tracks made by off-road vehicles that are deep enough to contain standing water will probably not be revegetated for many years. The adverse effect in these instances is primarily aesthetic since a relatively small amount of habitat has been affected.

Human Occupation

The existence of a large work force on Amchitka over a period of several years (1966 to 1973) had identifiable ecologic consequences. During the periods of peak activity, i.e., during the preparation for the Milrow and Cannikin tests, the total work force numbered over 700. Housing, messing, and laboratory and shop facilities were provided at the Main Camp, at Huskey Camp, and in several warehouses and shops located near Baker Runway and Constantine Harbor. In addition, a smaller camp facility, control point, and fallout shelter were constructed near the north end of the island for occupation during the execution of the Milrow and Cannikin tests. All three camps were established on areas previously disturbed during World War II or Long Shot.

Waste Disposal. Lagoons were constructed to receive sewage from Huskey Camp and from the Main Camp. The outfall from the Main Camp lagoon flows into a small lake and thence into a short stream running to the Pacific coast. Enrichment of the lake water resulted in dense blooms of blue-green algae and, in 1972, a rate of primary productivity many times as high as that of most undisturbed lakes on the island (see Burkett, Chap. 13, this volume). Productivity measurements made in spring and fall of 1974, after the work force had departed, yielded values more typical of uncontaminated lakes on the island (Kirkwood,

1975). The lagoon for the Huskey Camp drains into a stream running into the head of Constantine Harbor. Although no measurements reflecting effects of pollutants were made, it can be assumed that nutrient enrichment also affected the biota of this stream. Natural flushing will probably remove the sewage wastes from these two watersheds, but we cannot predict how long this may take. Burkett (Chap. 13, this volume) found heavy blooms of blue-green algae in other lakes in the part of the island densely inhabited by troops during World War II and theorized that nutrient enrichment of these lakes might be attributable to leachate from pit toilets used during the military occupation.

A garbage-disposal area for the AEC Main Camp was established near the camp on the site of a World War II trash dump. Garbage and other camp wastes were periodically covered by bulldozer, but the food scraps at the dump still attracted large numbers of Bald Eagles, gulls, and rats. Sherrod (1975) reported that the garbage dump was an important food source for Bald Eagles during the AEC occupation, especially during the winters. He speculated that the existence of this supplementary food source affected the composition and distribution of the Bald Eagle nesting population on Amchitka over the period 1969 to 1972. His evidence indicated that the abundant food supply during this period permitted more birds to reach adulthood and to nest on the island. This finding is corroborated by the slightly greater concentration of active nest sites in the southeastern third of the island where the dump was located. Estimates made in May 1974 indicate that the total Bald Eagle population was then about 38% less than the average for 1969 to 1972, or 175 versus 281 (Kirkwood, 1974). The population drop was greatest (63%) among immature birds.

No data are available on the influence, if any, of the dump on the gull population, although observations indicated that it was a feeding place for many gulls. It was also observed that, after the dump closed, the change in the adult-to-immature ratio for gulls was similar to that for eagles (C. M. White, personal communication).

Recreational Activities. Sport fishing, an important form of recreation for island personnel during the AEC occupation, produced some impact on the freshwater ecosystem. Fishing pressure was heavy on anadromous Dolly Varden and pink salmon returning to freshwater streams to spawn. Valdez et al. (Chap. 14, this volume) noted that salmon runs into Amchitka streams, which are meager at best and very vulnerable because streams

*Twenty-five round trips in June, July, August, and September over the 3 years (R. A. Valdez, personal communication).

are small and shallow, suffered from the efforts of overzealous fishermen. It will be some years before a definitive assessment can be made of this potentially long-term effect of human predation on spawning salmon.

What is perhaps a more ecologically significant perturbation from recreational activity was the deliberate stocking of some freshwaters with anadromous Dolly Varden taken from streams with access to the sea. The extent of this sort of manipulation cannot be documented, but hearsay information collected by the freshwater biologists indicates that the practice was fairly common. This explains why certain landlocked ponds were found to contain Dolly Varden with the morphological characteristics of the anadromous type. It is not known whether genetic differences exist between landlocked and anadromous populations of Dolly Varden. If they do, the opportunity for genetic mixing may have obliterated the differences in cases where the two forms have been brought together by stocking.

IMPACTS OF NUCLEAR DETONATIONS

The prompt bioenvironmental effects of the Milrow and Cannikin detonations are described in detail in the references cited previously. Such effects will be treated here only in summary form; the emphasis will be primarily on results of studies conducted since the tests to monitor long-term effects and recovery from initial disturbances (Kirkwood, 1974; 1975; Nelson, 1975).

Physical and Biological Effects of Milrow

A nuclear device of less than 1 Mt yield was detonated at Site B on Oct. 2, 1969. The shot point was about 1218 m (4000 ft) below SZ. The Milrow test was carried out as a "calibration shot" to evaluate the feasibility of conducting a higher yield test at Amchitka and to improve capabilities for predicting the effects of the proposed larger test. Extensive field observations, test-time experiments, and measurements were conducted in connection with the Milrow event. Late pretest and early posttest visual surveys, sample collections, and photography were used to identify effects of the detonation on the island terrain and biota. Follow-up studies have continued in those few areas where persistent changes attributable to the detonation were detected.

Ground motion from the Milrow shot produced some persistent effects in the bioenvironment, the most notable of which were rockfalls and turf falls along both coasts, the explosive disruption of a few turf mounds near SZ, and a

slight vertical movement along one side of a fault line extending across the intertidal bench on the Pacific Ocean coast. Chimney collapse after the event partially drained two lakes close to SZ and produced some cracking and fissuring in the tundra mantle in the vicinity of SZ.

Coastal Rockfalls and Turf Falls. Rockfalls estimated to comprise at least 6900 m³* occurred along the coasts, most of them from cliffs within 4 km (2.5 miles) of Milrow SZ. Over 70% of the total is accounted for in a single fall in Square Bay on the Bering Sea coast; most of the balance was distributed along a 4-km (2.5-mile) section of the Pacific shoreline near the Milrow site. Although rockfalls occurred in the vicinity of one falcon eyrie and from one sea stack occupied by an eagle nest, both nest sites were later used by these nesting raptors. However, the eagle nest was not usable after 1973 (C. M. White, personal communication). Small turf falls were widely scattered along both coasts. In a sense the Milrow ground motion accelerated the normal attrition of the peat mantle that overhangs many of the cliff tops and extends part way down the unstable cliff slopes.

The ecological consequences of localized rockfalls and turf falls were negligible. Small areas of habitat in the high intertidal zone were buried, and the algae and invertebrates inhabiting them were smothered. However, the areas so affected are too small to have any real impact on the extensive intertidal marine communities that surround the island. The fallen material is gradually being eroded away by wave action or becoming stabilized in the new location. When enough erosion occurs to restore intertidal conditions, a typical intertidal flora and fauna will again become established.

Fault Shift. A slight and apparently recent shift along a preexisting fault line extending across the intertidal rock bench, at Duck Cove on the Pacific Ocean coast, was first recognized in the spring of 1970, about 6 months after the Milrow test. The evidence suggested that the movement was triggered by Milrow. Along the fault line, which extends across an intertidal bench about 100 m (330 ft) wide, the average vertical displacement on the uplifted side was estimated to have been about 12 cm (5 in.). The bench is believed to have been unmoved on the other side of the fault (see Chap. 17, Fig. 20, this volume). The slight vertical displacement, which occurred in an intertidal zone where elevation is a critical factor influencing survival of algae and associated invertebrates, produced recognizable changes in the algal

*The estimate was originally 10,000 m³, but later studies led to the lower estimate (Kirkwood, 1974).

cover. In the area of maximum uplift, immediately adjacent to the fault, algae of some species died and were ultimately removed by wave action. The exposed bench has since been recolonized by species of algae adapted to the new elevation or remains bare in places. Erosion of bare areas is continuing (R. G. F., personal observation, 1975). The area over which composition of the algal cover was affected to some degree has been estimated to be about 4 ha (10 acres), although the area exhibiting extensive die-off was considerably smaller (Lebednik, 1973; Lebednik and Palmisano, Chap. 17, this volume). Populations of marine invertebrates associated with the plant cover have also undergone some shifts in composition as a consequence of the uplift and resultant changes in cover (Burgner and Nakatani, 1972).

The uplifted intertidal area, especially the portion subjected to maximum displacement, has been the subject of intensive study, perhaps because it is the only identified instance of a persistent effect in the marine environment attributable to the Milrow detonation. The studies demonstrate the not surprising sensitivity of intertidal benthic communities to changes in elevation, however slight. A new stable community of algae and invertebrates is gradually becoming established on the uplifted bench, and no long-range ecological consequences of the uplift have been identified (Lebednik and Palmisano, Chap. 17, this volume).

Terrain Disturbances. A highly visible terrain effect of the Milrow ground motion was the explosive disruption of a few natural tundra mounds within about 1.5 km (4900 ft) of SZ. Large blocks of peat that had been ejected from the mounds fell back in random orientations. Vegetation, mainly grasses, is becoming established on the freshly exposed surfaces (Everett and Amundsen, 1975).

Chimney collapse, which took place about 37 hr after the Milrow detonation, produced a shallow rectilinear depression about 540 m (1770 ft) across, centered on SZ, and about 6.1 m (20 ft) deep at its deepest point (Morris and Gard, 1970). Two lakes located partly within the perimeter of the depression were tilted toward SZ and partially drained by tilting and by fissuring of the lake bottoms. The lakes remain only partially filled, and in 1975, 6 years after the test, the fissures were still clearly visible. Vegetative cover is developing on the exposed bottom; the cover is heaviest where the substrate is peat and sparse where it is rocky mineral soil. Within and outside the depression, chimney collapse caused many tears and fractures in the peat mantle, in some instances leaving vertical scarps up to 1.5 m (5 ft) high. These

fractures and scarps will remain visible for many years.

Effects in the Freshwater Ecosystem. The shock wave generated by the Milrow detonation killed many threespine sticklebacks in two freshwater ponds within 930 m (3050 ft) of SZ (Neuhold, Helm, and Valdez, 1971). Sympatric populations of Dolly Varden were not affected. Autopsy of sticklebacks found dead in these ponds after the test revealed ruptured swim bladders, internal hemorrhaging, and pale gill filaments, symptoms believed to have been due to the rapid pressure changes accompanying the passage of the shock wave through the ponds. A few sticklebacks were also killed by stranding after they had been thrown ashore with the lake water as the shock wave passed. Some unharmed threespine sticklebacks survived in the lakes where fish kills were observed, and normal reproduction by the surviving sticklebacks was observed in 1970 in Clam Lake, about 600 m (2000 ft) from SZ, where the greatest mortality had occurred (Neuhold et al., 1971). No persistent effects on the populations of threespine sticklebacks can be attributed to Milrow.

Transient changes in stream flow rates, increased turbidity in freshwaters, and altered lake levels were also noted shortly after the detonation. These are detailed in reports referred to earlier and need no further discussion here. None was persistent or of recognizable consequence in the freshwater ecosystem.

Marine Mammals and Fish. Populations of marine mammals found around Amchitka (sea otters, sea lions, seals, and porpoises) were not detectably affected by the Milrow test. Three days after the test, a single dead porpoise was found on the Bering Sea coast about 3.2 km (2 miles) from SZ. Death was due to penetration of the animal's lung by a fractured rib, and the injury is not believed attributable to Milrow. No other dead or injured marine mammals were seen in posttest surveys. No effect of Milrow on marine fish populations was detected in comparing pretest and posttest catches made off Amchitka with standard fishing gear (Kirkwood, 1970).

Physical and Biological Effects of Cannikin

A nuclear device of approximately 5 Mt explosive yield was detonated at Site C on Nov. 6, 1971. The shot point was 1790 m (5875 ft) below SZ. Prompt effects were evaluated through late pretest and early posttest measurements, extensive posttest surveys, and some test-time experiments. Extremely adverse weather just before the test prevented the execution of some planned experiments.

The physical effects of the Cannikin test were similar to those of Milrow but were generally more severe, as was predicted from the greater explosive yield of Cannikin. They included coastal rockfalls and turf falls, uplift of a section of intertidal bench on the Bering Sea coast, and creation of a large subsidence depression accompanied by drainage of ponds and formation of scarps and fissures in and around the depressed area.

Effects on fauna were much more severe than those attributable to Milrow. Large numbers of animals, including fish, marine mammals, and some birds, were estimated to have been killed in the marine, freshwater, and terrestrial ecosystems.

Coastal Rockfalls and Turf Falls. Coastal rockfalls and turf falls were greatest along the Bering Sea coast in a section about 7.5 km (4.7 miles) long. It was estimated that within this sector about 30,000 m³ of rock and turf fell from the coastal cliffs (see Figs. 2 and 3). The greater part of the total is accounted for in large slides and falls in a 2-km (1-mile) sector adjacent to SZ between Sand Beach Cove and Banjo Point. On the Pacific coast, opposite Cannikin SZ, rockfalls and turf falls were estimated to total about 5000 m³.* These falls had the effect of smothering marine life in the high intertidal zone in some sections of the coast and of destroying, at least temporarily, the upper intertidal habitat in the same sections. Most of the material thrown down was deposited shoreward of the intertidal zone, thus affecting intertidal biota only in very localized areas (O'Clair, Chap. 18, this volume). Where material fell into the intertidal zone, wave action will, in most cases, eventually remove the debris and restore the habitat.

The rockfalls and turf falls, which were most severe on narrow headlands, destroyed four Bald Eagle nesting sites on the Bering Sea coast and two on the Pacific Ocean coast (see Fig. 4). The total number of nests occupied by Bald Eagles on Amchitka during four breeding seasons were 57 in 1969, 56 in 1970, 68 in 1971, and 71 in 1972 (Sherrod, 1975). These data show that the loss of six nest sites had no detectable effect on the number of nesting attempts by Bald Eagles during the first breeding season after Cannikin.

Three Peregrine Falcon eyries were destroyed or damaged on the Bering Sea coast. Concerning these, Williamson and White (1974) concluded:

"Three falcon nest sites were unusable as a result of the testing program. The rubble was cleared from one of these in 1972, however, and it was used successfully in 1973. The other two sites had been used irregularly by a single pair in previous years, and that pair successfully occupied another site in 1972 and 1973. Thus the Peregrine Falcon population was essentially unaffected by short term effects of AEC activities."

Fault Shift. A section of intertidal bench on the Bering Sea coast was displaced upward with effects similar to but more severe than those observed on the Pacific Ocean coast after Milrow. The maximum uplift occurred in a "...1.9-km (1.2-mi) sector immediately to the east of Sand Beach Cove, on the Bering Sea coast. Here vertical displacements of 25 to 107 cm (10 to 42 in) were measured" (Kirkwood and Fuller, 1972, Table A-5) (Fig. 22, Chap. 17, this volume, shows a view of the area of greatest uplift). Uplifting of 18 cm (7 in.) or more occurred along a 3-km (2-mile) section of coast extending southeastward from the point of maximum displacement (Merritt, 1973). Some uplift also took place to the northwest of the area of maximum uplift, as indicated by detectable die-off of some intertidal algae during the 1972 growing season following Cannikin (Lebednik and Palmisano, Chap. 17, this volume).

Quantitative studies on the effect of displacement on marine algae and invertebrates have been concentrated in the area of greatest displacement, i.e., on study plots established pretest in the 0.5-km (0.3-mile) section of coast just east of Sand Beach Cove. Algae and invertebrates that remain in the intertidal zone, albeit at higher levels than before, have exhibited varying degrees of die-off and changes in community composition (Lebednik and Palmisano, Chap. 17 and O'Clair, Chap. 18, this volume).

In parts of the uplifted area, the development of a stable intertidal community has been prevented by continued erosion and siltation. Climax communities will not be established until the substrate becomes stabilized, a condition that may not be reached for several years. The ultimate status anticipated for those areas has been described as follows: "There is little doubt that eventually the vegetation in these areas remaining in tidal influence should accommodate to the new levels and a normal vegetation, for that level, should occur" (Nakatani and Burgner, 1974). The same judgment would, of course, apply to invertebrates associated with the vegetation.

O'Clair (Chap. 18, this volume) estimated that, between Sand Beach Cove and Banjo Point, the coastal sector of maximum displacement, about

*The volumes of rockfalls and turf falls were initially reported as 25,000 m³ on the Bering Sea coast and 2000 m³ on the Pacific Ocean coast (Kirkwood and Fuller, 1972). These values were later revised upward to those cited here (Kirkwood, 1974).

Fig. 2—Map showing precollapse and postcollapse fracturing and surficial disturbances resulting from the Cannikin event. (From Merritt, 1973; adapted from Morris and Snyder, 1972.)

Fig. 3—Rockfall on Bering Sea coast resulting from Cannikin-generated ground motion. (Photograph by T. R. Merrell, Jr., National Marine Fisheries Service.)

5.8 ha* (14 acres) of intertidal bench was lifted into the supralittoral fringe zone. This area will not be recolonized by marine forms until erosion restores it to the intertidal zone. The net loss of intertidal habitat is believed to be somewhat less than 5.8 ha since some undetermined amount of bottom has also been uplifted from the subtidal level into the intertidal zone.

Outside the areas of intensive study (and maximum uplift), data on effects of uplift are limited to subjective evaluation based on observations made along the shore. These observations indicate that intertidal algae were affected to some degree along about 6.1 km (3.8 miles) of shoreline. Die-off was characterized as detectable along 2.7 km (1.7 miles) of coast, moderate along 1.5 km

(0.9 mile), and severe along 1.9 km (1.2 miles) (Lebednik and Palmisano, Chap. 17, this volume). The 1.9-km section of maximum disturbance constitutes only a little more than 1% of the approximately 171-km (106-mile) coastline of Amchitka, much of which has intertidal bench habitat similar to that displaced by Cannikin. The effects of uplift on the intertidal communities, though locally severe, cannot be said to have had any ecologically significant effects on the island ecosystem.

In early post-Cannikin surveys, divers observed some physical disturbance in the shallow subtidal zone off Sand Beach Cove. Numerous large blocks were broken from the bedrock or dislodged from vertical bottom surfaces, with consequent disturbance of algae and invertebrates occupying this habitat (Kirkwood and Fuller, 1972). By August 1974 most of the newly exposed rock surfaces had been recolonized and differed from nearby undisturbed surfaces only in that individual algae plants

*This area was earlier reported as 57.6 ha (143 acres) (Kirkwood, 1975). A recent recheck of the data has shown that the original estimate was too large by a factor of 10 owing to a computational error.

Fig. 4—Sea stack on Pacific Ocean coast where eagle nest site was destroyed by Cannikin-generated ground motion. (Photograph by Pan American, Las Vegas, Nevada.)

were smaller, presumably because they were younger than those which escaped disturbance (Kirkwood, 1974). The ecological consequences of these localized subtidal disturbances were minor and transient.

Marine Mammals and Fish. Substantial numbers of fish and marine mammals, principally sea otters, are estimated to have been killed by the Cannikin test along the Bering Sea coast and in the sea adjacent to the coast opposite SZ. To a large degree these estimates are based on comparison of pretest and posttest counts (sea otters) or catch statistics (marine fish) rather than on actual recovery or observations of dead animals. They are the best estimates available and are believed to reflect fairly accurately the general magnitude of the kills.

Twenty-one dead or injured sea otters and two abandoned otter pups were recovered or observed in post-Cannikin searches. Autopsies were performed on 12 of the animals recovered; carcasses

(or skeletons) of the other 9 adults were too badly deteriorated when found to justify autopsy. It was judged that 10 of the animals autopsied had lesions caused by sharp transient pressure pulses in the water with the passage of the shock wave, whereas 2 were crushed by falling rocks (Rausch, 1973).

The animals recovered are thought to represent only a small fraction of the total number of otters killed by Cannikin, as judged by comparison of pretest and posttest counts of otters along the Bering Sea coast adjacent to SZ. For a number of reasons, the absolute number of animals that may have been killed is very difficult to estimate. A count made along a 16-km (10-mile) sector of Bering Sea coast about 2 weeks after Cannikin showed a drop of 87% from the previous peak count made on the same coastal sector in June 1971, a drop from 1206 to 153. The significance of this change is hard to interpret, given the difference in season and in counting conditions. In August 1972, under comparable conditions, 521

animals were counted in the same sector, a reduction of 57% from the pre-Cannikin count. These data can be interpreted to mean that, out of a population estimated at over 6000 animals, several hundred sea otters may have been killed by the Cannikin detonation. Estes and Smith (1973), who reported both the pre- and post-Cannikin counts and the population estimates for the island, concluded that "The Amchitka sea otter population will suffer no long-term effects from Cannikin."

Four dead or injured harbor seals were found after the Cannikin test. Autopsies showed that they also had suffered the effects of rapid pressure change in the water (Rausch, 1973). No attempt has been made to estimate the number of seals killed by the test, but the Amchitka seal population is not believed to have been affected in any long-term sense by the detonation.

The only direct evidence of a substantial kill of marine fish by the Cannikin test was found along a 3-km (2-mile) section of Bering Sea coast adjacent to SZ. Along this section of beach, posttest searches recovered nearly 300 dead rock greenling, a fish common in the nearshore habitat and one that characteristically feeds over the intertidal bench during high tide. Autopsies indicated that the greenling were killed either by stranding on the uplifted portion of the bench or possibly by physical damage resulting from vertical acceleration of the bottom with passage of the shock wave. Further evidence of a localized kill of rock greenling was provided by the comparison of pretest and posttest trammel net catches in nearshore Bering Sea waters immediately adjacent to Cannikin SZ. Catches per unit fishing effort declined sharply immediately after the test, although evidence of recovery was seen within about 2 weeks after the event. By the early fall of 1972, less than 1 year posttest, catches of rock greenling were equal to those recorded before the test (see Chap. 19, Fig. 12, this volume). There is no reason to believe that this transient and localized decline in the rock greenling population had significant ecologic consequences. Greenling play a small part in the diet of the sea otter and perhaps of some sea birds (Kenyon, 1969; Nakatani and Burgner, 1974), but neither otters nor sea birds are sufficiently dependent on them to have been affected by a temporary reduction in availability of this food item.

Catches of rock sole in bottom trawls off the Bering Sea coast adjacent to Cannikin SZ showed a substantial decline after the test compared to pretest catches. This was interpreted to have been the consequence of a "large localized mortality" of rock sole attributable to Cannikin (Nakatani, Isak-

son, and Burgner, 1973), although the data do not provide an adequate basis for quantifying the presumed kill. A year after the test, bottom-trawl catches of rock sole in the affected area were not significantly different from pretest catches; this recovery of the population is assumed to have occurred by immigration from nearby unaffected areas (Nakatani and Burgner, 1974).

The prompt recovery of local populations of rock greenling and rock sole, the only two species of marine fish known to have been affected significantly by Cannikin, suggests that no irreversible or long-term adverse effects on fish in the marine ecosystem resulted from the Cannikin event. The rapid recovery of these two populations also argues against the likelihood of any important secondary ecological effects resulting from the temporary decline in numbers of rock greenling and rock sole or of any other fish species that may have been affected in the marine environment off Amchitka.

Effects on Birds. Post-Cannikin searches recovered 16 dead birds, all aquatic types, 15 of which are thought to have been killed by the test. Eight were judged to have been killed by vertical acceleration damage while they perched on shoreline rocks and seven by pressure pulses while they were in the water (Rausch, 1973). Four of the dead birds were found on the Pacific Ocean coast and eleven on the Bering Sea coast. It is believed that only a fraction of the aquatic birds killed by Cannikin were recovered, owing to adverse wind and sea conditions prevailing following the test. However, comparison of pretest and posttest counts of representative species indicated no detectable test-related declines in avian populations (Kirkwood and Fuller, 1972).

Short-term effects of the loss of a few raptor nest sites, mentioned above, and the death of a small number of aquatic birds appear to have been of little ecological significance. As noted by White et al. (Chap. 11, this volume), long-term effects on avian populations would be detectable only after 5 to 10 years (one generation time for eagles and falcons). In view of the small percentage of the potential raptor nesting sites on Amchitka that was affected, the likelihood of long-term effects on raptor populations seems slight.

Effects in the Freshwater Ecosystem. The effects of the Cannikin detonation in freshwater lakes and streams included complete or partial drainage of some lakes, increases in particulates in ponds close to SZ, fish kills in close-in lakes, and changes in the stream drainage pattern near SZ which resulted in the creation of a large lake where none had existed before. Six small lakes and ponds

Fig. 5—Fissure in bottom of pond east of Cannikin SZ which was drained by Cannikin-generated ground motion. (Photograph by T. R. Merrell, Jr., National Marine Fisheries Service.)

were completely or partially drained by fissuring of the bottoms and by tilting that occurred when a collapse crater formed about 38 hr after the detonation (see Fig. 5) [see Morris and Snyder (1972) for a detailed description of the collapse depression and location of the lakes affected by it]. The drained ponds lie within about 1.2 km (0.7 mile) of SZ and altogether amount to less than 10 ha (25 acres) in area. Several lakes within 2.2 km (1.4 miles) of SZ showed transient increases in particulate organic matter after Cannikin, probably the result of bank slumping and suspension of bottom sediments owing to ground motion.

An estimated 10,000 threespine sticklebacks and 700 Dolly Varden were killed by Cannikin, all within a radius of 1.8 km (1.1 miles) from SZ. Most of the fish were killed by stranding in the drained lakes and ponds; a few were killed by pressure pulses or by being thrown onto shore with passage of the shock wave.

The subsidence crater that formed with chimney collapse after the detonation captured the drainages of the two branches of White Alice Creek, and, for a little over a year after the test, stream flow in the lower reaches of this creek was sharply reduced (Gonzalez, Wollitz, and Brethauer, 1974; Dudley et al., Chap. 3, this vol-

ume). By Dec. 1, 1972, the lake that had been forming within the subsidence crater, now named Cannikin Lake, had reached its highest level and had begun to spill into White Alice Creek. Cannikin Lake, with an area of 12 ha (30 acres) and a maximum depth of 9.45 m (31 ft), is by far the deepest lake on Amchitka and has a larger volume than any other lake on the island (see Chap. 3, Figs. 5 and 6, this volume). This lake and the subsidence sink that surrounds it comprise the most conspicuous terrain disturbance attributable to Cannikin. Near the lake outlet, White Alice Creek now flows in a meandering course of low gradient over a firm peat bottom. Cannikin Lake will likely retain its present shoreline and depth for many decades [see Gonzalez et al. (1974) for a detailed description of the bathymetry of Cannikin Lake].

Follow-up studies indicate that Cannikin Lake is developing a planktonic flora and fauna typical of freshwater lakes on Amchitka; water-chemistry values for the lake are also within the spectrum of values found in nearby natural lakes. Productivity measured in autumn 1973 was equal to or higher than that of all but the most productive (nutrient-enriched) lakes on the island (Burkett, Chap. 13, this volume). By August 1973 small Dolly Varden were present in the lake. Specimens caught by gill-netting were judged to be of the dwarf or landlocked form, indicating that they were recruited from stocks residing in White Alice Creek, which is not accessible to anadromous fish. One year later the lake was found to contain a population of Dolly Varden of a size that suggested they could not have developed from the landlocked White Alice Creek stock. Subsequently it was learned that in 1973 workmen on the island had introduced a number of anadromous Dolly Varden into Cannikin Lake. The opportunity for studying the development of a landlocked Dolly Varden population, suddenly given access to a relatively large and deep lake habitat, has thus unfortunately been lost.

It is too early to determine what long-term effects the creation of Cannikin Lake may have on the Amchitka ecosystems. Certainly the new lake, in terms of depth and volume, is a feature different from any of the ponds and lakes that existed on the island before Cannikin and hence provides a new sort of freshwater habitat. It will be years, or decades, before we can know whether or not this habitat will develop a biotic community different from those found in the shallower natural lakes.

Terrain Disturbances. Terrestrial habitat disturbances caused by Cannikin were similar to those attributable to Milrow although somewhat more severe. The physical changes in terrain are detailed

in Merritt (1973) and Morris and Snyder (1972). An extensive system of surficial cracks and tears disrupted the tundra mantle in the vicinity of SZ (see Fig. 2). Some of this terrain disturbance was produced directly by ground motion from the detonation, but by far the greatest amount occurred with collapse of the chimney and formation of the subsidence sink (Fig. 6). Vertical scarps ranging up to 3 m (10 ft) in height bound the deepest part of the sink. Most of the other fractures and tears in the tundra mantle are within these bounding fractures, but lesser fractures, scarps, and tears in the mantle are found outside the depression at distances up to 2.5 km (1.6 miles) from SZ. The fractures and scarps will remain as recognizable terrain features for many decades, although the freshly exposed peat surfaces will eventually be covered with vegetation (some within a few years, as judged by recovery of peat substrates exposed by ground shock from Milrow).

Except for the 12 ha (30 acres) of former meadow habitat now inundated by Cannikin Lake, the amount of terrestrial habitat actually destroyed by Cannikin was small. Everett and Amundsen (1975) estimated that, in the area most affected by the Cannikin detonation [a circular area of 1000-m (3280-ft) radius centered 400 m (1300 ft) ENE of SZ], a reduction of about 5900 kg in annual production would be expected (about 4% of the total annual production for the area). This represents a loss of the production of about 14.5 ha (36 acres), or less than 0.05% of the total area of Amchitka. The area covered by Cannikin Lake accounts for most of this; the balance represents losses from scattered turf slides and related surficial disturbances. The terrain scars are, of course, readily visible and will remain so for a long time, even though the basic productivity of the terrestrial ecosystem in the vicinity of SZ is altered only slightly.

CLEANUP AND RESTORATION

During 1972 and 1973 the AEC and its contractors carried out a demobilization and restoration program on Amchitka. The objectives were to remove all AEC-constructed equipment and facilities except for those items needed to support the long-term monitoring program or those requested by the U. S. Department of the Interior and to, "insofar as practical, take the actions which will allow for and enhance the natural restoration of land areas disturbed by AEC activities" (Nevada Operations Office, Las Vegas, Nev., personal communication). The program included cleanup and restoration of the Long Shot site, although the Long Shot test was not actually a part of the

Fig. 6—Fracture through tundra southeast of Cannikin SZ produced by chimney collapse after the event. Vertical scarp in right foreground is about 1.3 m (4 ft) high. (Photograph by T. R. Merrell, Jr., National Marine Fisheries Service.)

recent AEC test series. Also, in compliance with the objectives of the Department of the Interior, some World War II facilities were destroyed or removed where this could be done without further disturbance to the landscape. Details of what was done under the demobilization and restoration program are given in Nevada Operations Office, 1974.

An island-wide cleanup disposed of waste materials and debris attributable to AEC activities and some debris remaining from World War II. The material collected was transported to a designated dump area. In connection with this cleanup, approximately 400 World War II structures were burned with fire-control equipment standing by to prevent spread of the fires. Salvageable equipment and facilities not needed for long-term monitoring efforts or requested by the Department of the Interior to be left in place were removed from the island.

Areas of terrain disturbance at drill sites, gravel pits, campsites, and other areas used during the AEC test program were graded and contoured to reduce erosion. In the summer of 1973, with the approval and guidance of the U. S. Fish and Wildlife Service, approximately 73.5 ha (182 acres) of prepared terrain was fertilized and seeded with a

mixture of four grasses (three perennials and one annual intended to serve as a nurse crop). The grasses and the fertilizer treatment were selected on the basis of revegetation studies conducted on Amchitka in 1971 and 1972 (Mitchell, 1976). The distribution of these plantings is as follows: Six drill sites, 39.6 ha (98 acres); four gravel pits, 16.5 ha (41 acres); campsites and miscellaneous disturbed areas, 17.4 ha (43 acres) (M. P. Curran, Holmes and Narver, Inc., Las Vegas, Nev., personal communication). (The condition of the Cannikin drill site 1 year after contouring and seeding can be seen in the foreground of Fig. 6, Chap. 3, this volume).

The grass seedings produced good vegetational cover at all locations, although in the summer of 1975 the vigor and density of the stands varied somewhat owing to the nature of the substrate and some apparent nonuniformities in fertilizer application. At most sites an initial heavy growth of annual ryegrass has left a mat of dead stems and leaves that now serves as a mulch and helps to retard erosion by water and wind. As of the summer of 1975, there was little evidence that native species were becoming established in the grass-seeded areas (R. G. F., personal observation). We believe that the seeded sites will be invaded by

native grasses and forbs as the mat of dead ryegrass decays, leaving bare areas between the clumps of perennial grasses.

One consequence of the seeding program, the introduction of a grass pathogen, *Corticium fuciforme*, to the island, was not anticipated. This fungal disease, commonly known as "pink patch," was first noted in August 1974 in grass seedlings made in August 1973 (Kirkwood, 1975). Positive identification was made by J. S. Hardison, U. S. Department of Agriculture, during the 1975 Task Force visit to Amchitka to study selected long-term effects and monitor for radioactivity. The route of transmission of *C. fuciforme* to the Amchitka seedlings is not known with certainty, but Hardison speculates that it probably came in the seed of one of the perennial grasses, a cultivar of *Festuca rubra* known as Boreal red fescue. It is not known whether this introduced pathogen poses any threat to native grasses on Amchitka, but Hardison did not find it on native grasses in the vicinity of the test plots in August 1975 (Nelson, 1975).

Not all the terrain disturbed by AEC activities was graded, contoured, and seeded. For a number of disturbed areas, especially at the northwest end of the island, U. S. Fish and Wildlife Service representatives concluded that revegetation with grasses would not be feasible or desirable, and the areas were only graded and contoured. In other situations, e.g., where predominantly organic spoil had been deposited, the U. S. Fish and Wildlife Service representatives believed that natural revegetation would take place at an acceptable rate, and no revegetation efforts were recommended (Carson Smith, Holmes and Narver, Inc., Las Vegas, Nevada, personal communication).

Drill holes, except for those few small-diameter holes left open for monitoring purposes, were either capped or plugged and then covered with concrete slabs. Drilling mud and supernatant liquid remain in holding ponds at Site D. During both the spring and fall Task Force visits to Amchitka in 1974, it was observed that drilling mud was leaking from these holding ponds. The retaining dikes were judged to be in poor condition and likely to break and release a major mud spill into Falls Creek (Kirkwood, 1974; 1975).

No leakage from the Site D ponds was observed during the August 1975 Task Force visit, and the dikes were still intact. Dike tops and outer faces had a good cover of seeded grass and appeared to be competent to hold the contents of the sumps. R. A. Brechbill, who saw the dikes in 1974 and in 1975, observed little change in their condition since fall 1974 (personal observation). Nevertheless, there still remains a strong possibility that the

dikes could breach (as a result of a seismic shock, for example) and release the contents of the sumps into Falls Creek. Experience with other mud spills at Amchitka suggests that such an event would cause severe, but probably transient, damage to the biota in the creek. Natural flushing action would remove the contaminants within a few months to a year, allowing the restoration of a normal stream biota from stocks in unaffected portions of the drainage.

SUMMARY

We have described the important specific impacts of the AEC nuclear test program at Amchitka and the efforts made to mitigate adverse effects. Additional details are given in the sources to which reference has been made. To assess the ecologic consequences of the various effects that have been identified, we must go beyond specifics. We must consider how much habitat has been destroyed or damaged, what loss of productivity has occurred, and how this loss is likely to affect the associated fauna. We must judge whether any biotic populations have been destroyed or endangered. Finally, since aesthetic values are an important feature of the natural ecosystem in a wildlife refuge, we must examine the impact of landscape disturbances on those values.

In the terrestrial environment, about 405 ha (1000 acres) of habitat was destroyed or severely disturbed by the combined effects of road improvement, construction, and drill-site preparation. About 74 ha (182 acres) has been partially restored by contouring and seeding to perennial grasses. The amount of terrestrial habitat lost as a result of the nuclear detonations has not been precisely quantified, but it is believed to consist mainly of the 12 ha (30 acres) of meadow submerged by the formation of Cannikin Lake plus a small additional loss from miscellaneous disturbances. The total amount of terrestrial habitat destroyed from whatever cause represents less than 1.5% of the total area of Amchitka. In terms of primary productivity in the terrestrial ecosystem, this loss also represents something less than 1.5% because part of the terrain disturbance took place in the northwest part of the island where the sparse vegetation is naturally less productive and because productivity has been restored to some extent on part of the severely disturbed area through seeding and fertilization.

The individual areas of terrain disturbance are small and dispersed; no type of habitat has been wholly lost from the terrestrial ecosystem. Some cliff tops and sea stacks, which form an important

nesting habitat for the raptor populations, have been damaged, but only a few nest sites formerly used by Peregrine Falcons and Bald Eagles have been rendered unusable. In all but a few instances, disturbed terrestrial habitat will undergo gradual restoration through stabilization of the substrate and reestablishment of vegetative cover. Altogether, we conclude that the loss of terrestrial habitat has been too slight to adversely affect the faunal populations using that habitat.

Some freshwater habitat has been destroyed by the drainage of several ponds, and some has been severely disturbed, as by the mud slide at Site E and releases of noxious drilling fluids and wastes into streams and ponds at other sites. McCann (1963) estimated that there are over 2100 lakes and ponds on the southeastern half of the island; of these, 8 have been partially or completely drained and about the same number have been affected to some degree by siltation or contamination with drilling effluents or human wastes. A few of the ponds were so badly contaminated that recovery will be very slow. In the others a fairly rapid recovery can be anticipated. Some 15 km (9 miles) of stream course has been affected to varying degrees. Most of this habitat will recover to its original status in a short time as normal stream-flushing action removes silt and other pollutants from the channels. One stream section about 1.3 km (0.8 mile) long below Site E has been altered in what we believe is an irreversible way by a massive mud slide. One new lake, deeper and with a greater volume than any natural lake on Amchitka, has resulted from the nuclear testing. All the changes in freshwaters attributable to the test program taken together involve only a small fraction of the total habitat of this type on Amchitka, and the perturbations are, in most cases, self-correcting. No long-term adverse ecologic consequences are foreseen from loss or damage to freshwater habitat.

Identifiable habitat loss in the marine environment was limited to small areas of the intertidal bench which were smothered by rockfalls and turf falls onto the upper fringe of the bench or were uplifted out of the intertidal zone owing to vertical movement between two fault lines. Effects were severe locally but of little overall consequence in view of the large amount of similar habitat around the island which remains unaffected. Natural processes of erosion, weathering, and establishment of flora and fauna adapted to the new conditions are already operating to restore the habitat lost in the nearshore marine environment.

No evidence has been found to indicate that any biotic population on Amchitka was lost or endangered as a consequence of the nuclear test

program. Substantial kills of sea otters and of freshwater and marine fish resulted from the Cannikin detonation. Subsequent studies showed a persistent drop in the sea otter population along only one section of Bering Sea coast; the effect on the overall sea otter population is believed to be a transient one. Marine fish stocks returned to their pre-Cannikin status within a year through normal reproduction and recruitment from unaffected stocks. In the freshwater ponds that were wholly drained as a result of the detonation or subsidence, the local stocks of landlocked Dolly Varden or threespine sticklebacks were lost. However, there is no reason to believe that populations in these ponds were different from those in many other similar ponds on the island; so Amchitka populations of landlocked Dolly Varden and sticklebacks cannot be said to have been endangered.

Whether salmon runs in some island streams have suffered a long-term decline as a consequence of the nuclear test program has not been determined. If 1970 counts are used as a base line, there has since that year been a reduction in the number of spawning pink salmon observed in a number of Amchitka streams. Since some of these streams could hardly have been affected by the test program, we cannot determine whether the decline of spawning in any stream system can be attributed to nuclear testing or to natural variations in spawning runs. There is no reason to believe that any stream formerly used by salmon has been rendered unsuitable for salmon spawning.

The AEC nuclear test program had adverse effects on the aesthetic quality of the Amchitka landscape wherever landforms were visibly altered by construction or by the nuclear detonations. The deterioration in aesthetic values was, in many instances, additive to clearly visible landscape scars dating from World War II; in other cases, e.g., at drill sites E, F, G, and H, parts of the island little affected by military occupation were scarred by the AEC operations. The landscape disturbances resulting from the nuclear test program are locally severe and apparent to the most casual observer, even where mitigated to some degree by the restoration efforts. Some of the scars will persist for decades or centuries to be healed eventually by natural processes.

In conclusion, the ecologic impact of nuclear testing at Amchitka has been slight when viewed in relation to the island as a whole. Deterioration of aesthetic quality in the terrestrial landscape constitutes the most important single effect, and this affects only a small part of the island terrain. Some adverse effects, notably those resulting from spills of drilling effluents, could and should have been avoided by the exercise of greater care in opera-

tions. Habitat deterioration in the terrestrial, freshwater, and marine environments, although locally severe, is not of long-term ecological consequence. Most biotic populations on and around the island have already essentially recovered from any adverse effects suffered as a result of the test program.

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Appendix A: Chronology

1964		1967	
February 4	Rat Island earthquake ($M_s = 7.75$).	January 13	DMA‡ authorizes construction. Population buildup for Milrow begins.
February 13–17	Party on Amchitka to investigate earthquake damage.	February	
April	Party on Amchitka to pick tentative Long Shot site.	Spring	Negotiations begin with various potential biological contractors.
May 5	U. S. Atomic Energy Commission (AEC) brought into Long Shot planning and program.	June	Reconnaissance by Battelle biologists.
May 16– December 14	Exploratory drilling and other field investigations to confirm site suitability for Long Shot.	June 2	Proposed biological program discussed with Interior.
December 23	Island evacuated.	Summer	ADFG§ sea otter harvest.
1965		July 1	Existing Battelle contract (for studies in Panama) modified to include Amchitka Bioenvironmental Program.
April 3	Population buildup for Long Shot begins.	August	General biological field work started.
June 2	AEC–DOD (Department of Defense) memorandum of agreement for Long Shot.	November 7	Conference with Interior and ADFG§ on sea otter.
October 12– November 2	LRB/UW* biologists in field for Long Shot biological program.	1968	
October 27	Device in place and stemmed.	January 29–31	Conference with Interior and State of Alaska on cooperation in sea otter transplants.
October 29	Long Shot detonated.	June 3– October 18	Archaeological site survey.
November 18– December 10	Project Breccia† field studies, including some biological studies.	Summer	ADFG§ sea otter transplant, with FWS¶ and AEC assistance.
December	Island evacuated.	September 24	Briefing on Amchitka Bioenvironmental Program for the Panel on Biological and Medical Sciences, Committee on Polar Research, National Academy of Sciences.
1966		All year	Biological field work; emphasis on base-line studies.
June 23	Site Selection Committee (SSC) starts looking for a high-yield supplemental nuclear test site in the lower 48 states.	1969	
August	More field studies for Project Breccia—20 people.	June 18	Public announcement of Milrow.
August	Permission granted by the Department of the Interior for use of Amchitka by the AEC.	Summer	ADFG§ sea otter transplant, with AEC assistance.
November 18	SSC duties expanded to include Amchitka.	September 25	President Nixon authorizes Milrow detonation.
November 30– December 6	Field reconnaissance by U. S. Geol. Survey—16 people.		

October 2	Milrow detonated.	May	Seismic stations removed.
All year	Biological field work; emphasis on pre- and post-Milrow studies.	May 19–21	Long Shot related holes sealed and abandoned.
1970		Summer	Retrograde shipments start.
May	ADFG § sea otter harvest.	September 19–26	All remaining holes sealed and abandoned.
June 12	Draft Environmental Statement for Cannikin issued.	All year	Biological field work; evaluation of Cannikin effects.
July	ADFG § sea otter transplant, with AEC assistance.	1973	
August 26–27	Symposium on Amchitka bio-environmental studies at AIBS meeting, Bloomington, Ind.	April 11	Work on this book starts with meeting of principals in Denver.
All year	Biological field studies; post-Milrow and pre-Cannikin studies.	Summer	Many disturbed areas recontoured and reseeded with grass; island cleanup and camp demobilization continues.
1971		September 8	Amchitka evacuated.
Spring	FWS¶ experiments with transplants of the Aleutian Canada Goose.	September	Control of Amchitka returned to Interior.
June	Final Environmental Statement for Cannikin issued.	All year until September	Biological field work; post-Cannikin studies.
June	ADFG § sea otter transplant, with AEC assistance.	1974	
October 27	Cannikin device in place, stemming starts.	May 2–June 1	Spring 1974 Scientific Task Force**—37 people.
October 29	President Nixon authorizes Cannikin detonation.	August 26–September 4	Fall 1974 Scientific Task Force**—30 people.
November 6	Supreme Court denies injunction against Cannikin; Cannikin detonated.	1975	
All year	Biological field work; emphasis on pre- and post-Cannikin studies.	August 8–September 9	1975 Scientific Task Force**—13 people.
1972		1976	
February 25	Postshot drilling for radiochemical samples completed; Amchitka cleanup starts.	February	FWS¶ puts small staff on Amchitka to rear Aleutian Canada Geese as the first step in reestablishment of a breeding population of these geese.
		August 10–18	1976 scientific party visits**—2 people.

*Laboratory of Radiation Biology, University of Washington.

†A military-sponsored investigation of possible surface indications of clandestine underground nuclear tests (reported in Shacklette et al., 1970).

‡Division of Military Application, U. S. Atomic Energy Commission.

§Alaska Department of Fish and Game. For details on sea otter transplants and harvests, see Abegglen, Chap. 20, this volume.

¶U. S. Fish and Wildlife Service, Department of the Interior.

**For continued evaluation of test effects and environmental monitoring for radioactivity.

Appendix B: Population History

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NOTICE

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Prepared by the Geological Survey for the United States
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Compiled in 1975 from AMS 1:25,000 scale maps and from
other official sources. See index for dates of individual maps.
Bathymetric contours 25 foot interval to 300 feet;
100 foot interval below 300 feet. Data provided by
Amodeo and Ivey, consulting geologists, Denver, Colo.
This information is not intended for navigational purposes.

Projection and 10,000-metre grid: Universal Transverse
Mercator, zone 60.
50,000-foot grid ticks based on Alaska coordinate
system zone 10.
1927 North American datum

Entire land area within Aleutian Islands National
Wildlife Refuge

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UTM GRID AND 1975 MAGNETIC NORTH
DECLINATION AT CENTER OF SHEET
LOCAL MAGNETIC DISTURBANCE
Differences of as much as 5° from the
normal declination have been observed
on Amchitka Island

CONTOUR INTERVAL 100 FEET
NATIONAL GEODETIC VERTICAL DATUM OF 1929
BATHYMETRIC CONTOURS IN FEET-DATUM IS MEAN LOWER LOW WATER
SHORELINE SHOWN REPRESENTS THE APPROXIMATE LINE OF MEAN HIGH WATER
THE MEAN RANGE OF TIDE IS NEGLECTABLE

GRID ZONE DESIGNATION 60U	TO GIVE A STANDARD REFERENCE ON THIS SHEET TO NEAREST 100 METERS
	SAMPLE POINT: 60U
60U	1. Locate the vertical grid line to the left of point and read LARGE figures indicating the value within the top or bottom margin.
	Estimate, within three grid line to point: 2. Locate the horizontal grid line below point and read LARGE figures indicating the value within the left or right margin.
60U	Estimate, within three grid line to point: 3. Estimate, within three grid line to point: 4. Estimate, within three grid line to point: 5. Estimate, within three grid line to point: 6. Estimate, within three grid line to point: 7. Estimate, within three grid line to point: 8. Estimate, within three grid line to point: 9. Estimate, within three grid line to point: 10. Estimate, within three grid line to point: 11. Estimate, within three grid line to point: 12. Estimate, within three grid line to point: 13. Estimate, within three grid line to point: 14. Estimate, within three grid line to point: 15. Estimate, within three grid line to point: 16. Estimate, within three grid line to point: 17. Estimate, within three grid line to point: 18. Estimate, within three grid line to point: 19. Estimate, within three grid line to point: 20. Estimate, within three grid line to point: 21. Estimate, within three grid line to point: 22. Estimate, within three grid line to point: 23. Estimate, within three grid line to point: 24. Estimate, within three grid line to point: 25. Estimate, within three grid line to point: 26. Estimate, within three grid line to point: 27. Estimate, within three grid line to point: 28. Estimate, within three grid line to point: 29. Estimate, within three grid line to point: 30. Estimate, within three grid line to point: 31. Estimate, within three grid line to point: 32. Estimate, within three grid line to point: 33. Estimate, within three grid line to point: 34. Estimate, within three grid line to point: 35. Estimate, within three grid line to point: 36. Estimate, within three grid line to point: 37. Estimate, within three grid line to point: 38. Estimate, within three grid line to point: 39. Estimate, within three grid line to point: 40. Estimate, within three grid line to point: 41. Estimate, within three grid line to point: 42. Estimate, within three grid line to point: 43. Estimate, within three grid line to point: 44. Estimate, within three grid line to point: 45. Estimate, within three grid line to point: 46. Estimate, within three grid line to point: 47. Estimate, within three grid line to point: 48. Estimate, within three grid line to point: 49. Estimate, within three grid line to point: 50. Estimate, within three grid line to point: 51. Estimate, within three grid line to point: 52. Estimate, within three grid line to point: 53. Estimate, within three grid line to point: 54. Estimate, within three grid line to point: 55. Estimate, within three grid line to point: 56. Estimate, within three grid line to point: 57. Estimate, within three grid line to point: 58. Estimate, within three grid line to point: 59. Estimate, within three grid line to point: 60. Estimate, within three grid line to point: 61. Estimate, within three grid line to point: 62. Estimate, within three grid line to point: 63. Estimate, within three grid line to point: 64. Estimate, within three grid line to point: 65. Estimate, within three grid line to point: 66. Estimate, within three grid line to point: 67. Estimate, within three grid line to point: 68. Estimate, within three grid line to point: 69. Estimate, within three grid line to point: 70. Estimate, within three grid line to point: 71. Estimate, within three grid line to point: 72. Estimate, within three grid line to point: 73. Estimate, within three grid line to point: 74. Estimate, within three grid line to point: 75. Estimate, within three grid line to point: 76. Estimate, within three grid line to point: 77. Estimate, within three grid line to point: 78. Estimate, within three grid line to point: 79. Estimate, within three grid line to point: 80. Estimate, within three grid line to point: 81. Estimate, within three grid line to point: 82. Estimate, within three grid line to point: 83. Estimate, within three grid line to point: 84. Estimate, within three grid line to point: 85. Estimate, within three grid line to point: 86. Estimate, within three grid line to point: 87. Estimate, within three grid line to point: 88. Estimate, within three grid line to point: 89. Estimate, within three grid line to point: 90. Estimate, within three grid line to point: 91. Estimate, within three grid line to point: 92. Estimate, within three grid line to point: 93. Estimate, within three grid line to point: 94. Estimate, within three grid line to point: 95. Estimate, within three grid line to point: 96. Estimate, within three grid line to point: 97. Estimate, within three grid line to point: 98. Estimate, within three grid line to point: 99. Estimate, within three grid line to point: 100. Estimate, within three grid line to point:

ROAD CLASSIFICATION
Light-duty road, hard or
improved surface

AMCHITKA ISLAND, ALASKA
N5115 - E17830/30460

SOILS MAP, AMCHITKA ISLAND, ALASKA

Validity (July, 1969)

Sea Otter Point

179° 10' E
51° 30' N

SOILS MAP, AMCHITKA ISLAND, ALASKA

Validity (July, 1969)

Crown Reefer Point

Banjo Pt.

Cannikin

Cyril Cove

Longshot

Ultra
Creek

Duck
Cove

Milrow

Rifle Range Pt. 51° 22' N

PLATE II Legend

- Soil group a_1
- Soil group a_2
- Soil group association a_2b
- Soil group b
- Soil group bh
- Soil group association bbh
- Soil group association bhb
- Soil group e
- Soil group association a_2bh
- Soil group association b,bh,a_2
- Soil group association c,ce
- Soil group association c,ce,b
- Soil group association c,ce,bh
- Thick mat
- Soil group h
- Disturbed area

0 500 1000 meters (approx.)

SOILS MAP,
AMCHITKA ISLAND, ALASKA
Validity (July, 1969)

179°00'E
51°37'N

PLATE III
Legend

- Soil group a_1
- Soil group a_2
- Soil group association a_2b
- Soil group b
- Soil group bh
- Soil group association bbh
- Soil group association bhb
- Soil group e
- Soil group association a_2bh
- Soil group association b,bh,a_2
- Soil group association c,ce
- Soil group association c,ce,b
- Soil group association c,ce,bh
- t Thick mat
- h Soil group h
- d Disturbed area

0 500 1000 meters (approx.)

SOILS MAP,
AMCHITKA ISLAND, ALASKA
Validity (July, 1969)