UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

Federal Center, Denver, Colorado 80225

GEOLOGIC AND HYDROLOGIC EFFECTS OF THE MILROW EVENT,
AMCHITKA ISLAND, ALEUTIAN ISLANDS, ALASKA

By

U.S. Geological Survey

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Amchitka-20
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U.S. Geological Survey

I. INTRODUCTION

By

L. M. Gard

The U.S. Geological Survey is conducting a program to determine geologic and hydrologic effects of the Milrow event. Milrow, an underground nuclear explosion of about 1 megaton, was fired at Amchitka Island on October 2, 1969.

The Geological Survey's studies include geologic effects, geodetic surveys, in situ rock-stress measurements, effects on the surface and subsurface hydrologic regime, and a preshot and postshot marine geophysical study. The principal factual data from the studies are presented in this report. However, many of these data are preliminary and analysis of them is incomplete.

Milrow was detonated at site B (fig. 1), which is situated on the eastern half of Amchitka Island at UTM coordinates N. 5,698,251.49, E. 651,750.61, zone 60. Collar elevation of the emplacement hole was 39.78 meters. The working point was about 1,218 meters below the surface (1,178 meters below sea level) in pillow lavas and breccias of Kirilof Point in the lower Tertiary Amchitka Formation.

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Figure 1.--Index map of Amchitka Island, Alaska. Letters indicate locations of exploratory drill sites. Milrow event was at site B.

II. VISIBLE GEOLOGIC EFFECTS

By

R. H. Morris and L. M. Gard

A postshot geologic inspection was made October 3-14, 1969 (D+1 to D+12), by a team of four geologists: L. M. Gard, F. N. Houser, R. H. Morris, and R. P. Snyder. An initial reconnaissance was made by Gard and F. W. Stead October 3-5 (D+1 to D+3) in an effort to observe and record ephemeral effects that might be obliterated by road grading and other repairs.

Two reconnaissance helicopter flights were made to assess effects on sea cliffs. From points near site C (fig. 1) the aerial inspection covered both coasts southeastward to St. Makarius Bay and Constantine Harbor, and as far northwest on the Bering Coast as Chitka Point, to inspect the ancient landslides near there.

Foot traverses were made along the several miles of the Bering and Pacific coastlines adjacent to the Milrow site, and examinations were made of roads, runways, taxiways, and known faults. A detailed study was made of GZ (ground zero) and the adjacent areas that extend out beyond the 2,000-foot-radius (610 meter) perimeter fence.

Visible geologic effects produced by the Milrow event were few and of limited extent; they include the typical effects such as rockfalls, turffalls, slumping, cracking, and soil disturbance--all similar to those effects associated with the Long Shot event on Amchitka in 1965. No old landslides were rejuvenated and no new ones were created.

Visible surface displacements and fractures were few and small when compared with those from similar-sized detonations at the Nevada Test Site. The paucity of cracks is due, at least in part, to the cover of turf and the underlying peat, which flexes instead of breaking and thus restricts bedrock exposures. Doubtless there are many fractures in the turf- and peat-covered bedrock that could not be seen.

Two fractures in the paved apron adjacent to Baker runway were visible: an L-shaped fracture occurring at the northwest corner of the runway was downdropped about 5 cm on the northwest side because of fill settling; and a curving hairline crack, which can be seen about halfway down the runway on the south side, had no vertical offset. Neither of these fractures involved the runway itself.

Two hairline cracks with no vertical offset cross normal to the taxiway south of Baker runway in the vicinity of Warehouse 2.

Faults

Although several known faults were examined along their traces and in outcrop, there was no surface indication of cracking and little indication of displacement along any of them.

The surface trace of the Rifle Range fault (fig. 8) trends N. 70° E. and is about 1,200 m south of the Milrow site. This fault has a natural stratigraphic displacement of about 1,220 m and probably is represented by a fractured zone as much as 300 m wide. The surface trace of this fault was traversed from coast to coast, but no visible evidence of surface fracturing or fault

offset was seen. The only visible explosion-produced effects along the surface trace were a turf slump about 46 meters long on the face of the fault scarp near a quarry 2.2 km east-southeast of GZ and an eruption of turf and peat 1.6 km south-southwest of GZ. Two small ponds lying along the fault trace 1.4 km SE of GZ displayed minor tilting towards GZ and evidence was seen that ground motion had thrown water out of these ponds away from GZ. No movement was observed on fractures that are extensions of the fault in the bedrock along the Pacific Coast.

Two roads cross the fault--Infantry Road near the center of the island and a newer unnamed road near the Pacific Coast. Although the Infantry Road fill was cracked where it crosses the fault scarp, none of these cracks was parallel to the fault; they were subparallel to the roadbed and are considered to be merely indications of the road fill slumping. Experience at the NTS (Nevada Test Site) has shown that compacted gravel or paved roadbeds being brittle will, where they cross faults, tend to show cracks parallel to the faults.

The road near the Pacific Coast was built on top of the turf and the underlying peat. Near where it crosses the Rifle Range fault the road exhibits two hairline cracks parallel to the strike of the fault.

On Kirilof Point, near the fuel tanks, the road was offset by a crack with a 15-cm-high scarp. This fracture, which trends N. 48° E., was downthrown on the southeast side and paralleled the linear valley that is thought to be a marine-eroded fault trace. However, this fracture could not be traced in the turf on either side of the road.

The closest explosion-produced fault scarp to GZ that is not directly related to subsidence at ground zero is about 710 meters south-southeast of GZ (fig. 7). This scarp, which strikes N. 63° E., has dropped the turf on the southeast side and can be traced for 450 meters along its strike. Prior to Milrow a fault was unknown here; however, the fault is in alinement with the linear scarplike southeastern shore of Silver Salmon Lake. This fault cuts across a small lake and has uplifted its north shore 46 cm.

A small fault of about 60 cm displacement, exposed in a cliff face 1,500 m west of GZ, moved down on the southeast side about 30 cm.

A SCUBA diver studying marine ecology in this same area reported a fresh 5-cm scarp in the sea bottom about 460 m offshore, but exact location, fault trend, extent, and direction of movement are not known.

Rockfalls

The most obvious physical effect of Milrow was the occurrence of numerous rockfalls along the Bering and Pacific Coasts. Steep-faced cliffs with zones of fractured rock or well-developed joint systems were particularly susceptible to the formation of rockfalls. This phenomena was especially true of, but not limited to, cliffs that faced away from the Milrow site--probably because of spall at the free-air interface.

The largest rockfall was at Square Bay where a cliff 30 m high and about 75 m long spalled off to a depth of as much as 6 m.

A more typical rockfall is shown in figure 2. It consists of roughly rectangular blocks formed by intersecting joint planes. The area photographed is along the Pacific Coast about 1.6 km southwest of GZ.

Slumps

Slumps formed in areas of unconsolidated to poorly consolidated deposits of sand and gravel, especially on steep slopes. The sand bluffs along the Bering Coast about 1.6 km west of Crown Reefer Point slumped. Some of the slumping occurred along the same planes as the slumps that resulted from Long Shot. Two views of the slumping are shown in figure 3.

At South Bight the bluffs are composed of poorly consolidated sand and gravel but showed little effect from the Milrow event. Random boulders and cobbles already loosened by normal erosion processes fell from the cliff face. The sandy talus at the base of the cliffs slumped only a minor amount, and in places the slumping produced hairline cracks (fig. 4).

Many slumps and slump cracks formed in the sand and gravel deposits exposed in borrow pits near Clevenger Lake and Fox Runway. Figure 5 shows slumps and slump cracks in glacial outwash exposed in a gravel pit near Clevenger Lake. Extensive slumping and cracking of the roadbed occurred along the northern shore of Clevenger Lake. The roadbed was constructed during World War II of compacted beach sand and gravel. This sand and gravel slumped towards the lake. Large open arcuate cracks as much as 1.5 m deep and trending obliquely

Figure 2.--Rockfall caused by Milrow. Rectangular blocks formed by intersecting joint planes. Location is 1.6 km southwest of Milrow GZ.

Figure 3.--Two views of slumping of unconsolidated sand in bluffs
1.6 km west of Crown Reefer Point.

Figure 4.--Milrow effects. A hairline crack formed by slumping of the sandy talus at the base of cliff, South Bight area. Note large boulders that were not shaken loose from cliff face.

Figure 5.--Slump and slump cracks, caused by Milrow, in glacial outwash exposed in gravel pit near Clevenger Lake.

across the road are shown in figure 6. This material was on a slope that faced radially away from the shot point and probably responded to spalling.

Fox Runway (fig. 8) and associated taxiways, which were built on unconsolidated Pleistocene outwash, showed cracks in the asphalt. Cracking of the pavement was first noted after the Rat Island earthquake of February 1965 when rusted culverts collapsed and the overlying pavement ruptured.

Soil disturbance

Areas within 2.5 km of ground zero, which lack vegetation cover generally because of construction, exhibit soil that has been disturbed by the ground motion.

Rocks lying on the ground surface in these bare areas as far as 6 km away from GZ commonly were displaced 1 m to several meters in a direction generally radially away from GZ. Rocks affected in this manner generally weighed more than 1 or 2 kg; rocks smaller than that normally were unaffected.

Turf disruptions

Randomly oriented cracks were noted in the turf within 700 m of GZ. These were as much as 15 cm wide and 60 m long and showed no apparent vertical offset. These cracks are thought to represent differential movement or shifting of the turf and peat blanket caused by the ground shock. Downhill migration of peat, even on nearly flat ground, is a natural process and healed cracks are common. On steeper slopes, naturally occurring cracks as much as 1.2 m wide, 15 m long, and 1.8 m deep have been observed; however, no cracks of these dimensions were caused by Milrow.

Figure 6.--Slumping of sand and gravel has produced cracks in road-bed near Clevenger Lake. Subgrade of World War II construction was beach sand and gravel.

Compression of the opposing banks of streams caused large mud geysers to form at shot time within 3.2 km of GZ; however, many turf banks as steep as 75° did not collapse.

In two places, 1,067 and 1,525 m from GZ (the latter being on the trace of the Rifle Range fault), areas of turf and peat as much as 15 m across erupted. The eruptions are thought to have been caused by hydraulic action in underlying saturated peat although the reason for their being localized at these places is unknown.

Massive natural landslides

Several known ancient landslides along the Bering Sea Coast were examined from the air. There was no indication that any of them had been reactivated by the Milrow event.

Long Shot site

The Long Shot site was examined thoroughly for evidence of renewed cracking or subsidence of the GZ area. Except for about 3 cm of lateral movement of the concrete pad around the emplacement hole, nothing was noticed to indicate rejuvenation of old fractures or subsidence. No new cracks were noted.

Depression in vicinity of Milrow GZ

About 37 hours after Milrow was fired, recording seismographs indicated collapse of the chimney. Prior to this time, postshot aerial photographs taken from a helicopter by Battelle Memorial Institute personnel showed no obvious fracturing or subsidence around GZ. With chimney collapse, however, the land surface sank as much as 6.1 m (Holmes and Narver, Inc., oral commun.) forming a depression of about 540 m across.

Figure 7 shows the major fractures in the vicinity of GZ. The most obvious of these fractures is the peripheral fault around the GZ depression. Instead of being roughly circular, as is common at the Nevada Test Site, this fracture is rectilinear and discontinuous. It is spectacular in that it passed through two lakes offsetting their bottoms, tilting them centripetally, and partially draining them. Where the excess water went is not yet known; some of the water formed two new ponds 200 m southeast of GZ, but the majority of water probably drained into the chimney through newly formed fractures (see section on Hydrologic Effects).

Maximum vertical offset on any fault occurred along the fault that is in the bottom of the lake west of GZ--there the lake bottom was downdropped 1.5 m on the GZ side of the peripheral fault. The presence of an ephemeral intermediate stage of shoreline, marked by stranded debris, could have been produced by: (1) a seiche when the lake tilted and dropped, (2) more than one stage of subsidence, or (3) marked increase in drainage of the lake into the chimney.

Other lakes near GZ tilted centripetally as shown on figure 7. Lakes unmarked on figure 7 may have tilted, but tilting was too slight to be detected visually.

Because the topography at the site slopes gently southward and because there are small swales draining southward into Clevenger Creek, it is doubtful that a lake will form in the GZ depression. An accurate and detailed topographic survey of the depression and the adjacent area should dispel any doubts.

Explanation

Explosion-produced fracture
Bar and ball on downthrown side.
Vertical displacement in centimeters

Direction of lake tilt

Tundra slump

Postshot lake shoreline

Ground zero.
Emplacement hole UA-2

Exploratory drill hole UAe-2

Figure 7.--Postshot fracture map, Site B, Milrow event.

Figure 7.--Postshot fracture map, Site B, Milrow event.

III. GROUND DISPLACEMENT MEASUREMENTS

By

F. A. McKeown, D. D. Dickey, and R. C. Bucknam

This section contains the factual data and very incomplete analysis of the measurements of ground displacement obtained by level-line surveys, geodimeter surveys, and tilt-of-lakes surveys. The most serious omission is that these data are generally not integrated with other kinds of information such as geologic, seismologic, photographic, and explosion phenomenology. The requirement to meet a deadline precluded the thorough study warranted by the amount of data already at hand.

In addition to the authors of this section, the following personnel of the U.S. Geological Survey assisted in making the geodimeter and tilt measurements: L. E. Bentley, C. H. Swanson, R. C. Foley, G. E. Brethauer, G. R. Terry, and W. L. Ellis. The level-line survey was made under the supervision of Holmes and Narver, Inc., and Owen Sammons in particular is to be thanked for the direction and coordination of the field activities of this survey. The level line was surveyed at the request of both the Sandia Laboratories and the U.S. Geological Survey.

Level-line survey

A level-line survey along Infantry Road was made from 6.5 km southeast of GZ to 8 km northwest of GZ (fig. 8). In addition, a line approximately through GZ and normal to the line along Infantry Road was surveyed.

Figure 8.—Map of part of Amchitka showing location of faults, strain grids, level line stations, stress probes, and lines of profile W-W', X-X', Y-Y', and Z-Z'

The accuracy of the survey is reported by Holmes & Narver, Inc. as follows:

"Considering the accuracy of the benchmarks, closures obtained and the short runs between benchmarks, the elevation could normally be considered accurate to the nearest .01 foot $\pm$.005 foot. However, because only one direction was run an accuracy of $\pm$.01 would probably be a safer assumption."

Considering such problems as the highly inclement weather and the unstable ground for benchmarks, the surveyors are to be commended for the accuracy they obtained.

The differences in elevation of each station in surveys made before and after the Milrow event are shown in profiles W-W', X-X', Y-Y', and Z-Z' (figs. 8, 9, 10, 11). Three different scales were used to show the survey data because of the large changes in elevation near GZ and the very small changes at distances beyond about 2 km.

In profile X-X' (fig. 9), the very definite lowering of elevation of about 2 cm towards point X from the fault 2 km southeast of the Rifle Range fault leaves little doubt that some movement must have occurred on that southeastern fault. It is also possible that movement on this fault caused some of the anomalous horizontal strains determined from strain grid C (fig. 8), which, in the profile X-X', is located astride the Constantine fault.

Movement along a fault is also indicated in profile Y-Y' (fig. 10). The doming that is apparent in this profile, and which resulted from the explosion, was perturbed by about 10 cm of displacement across a

Figure 9.--Profiles W-W' and X-X' showing faults and vertical displacements from pre- and post-Milrow surveys. Displacements and faults (dashed lines) are projected from road to lines of sections.

Figure 10.--Profile Y-Y' showing fault (dashed line), GZ, and vertical displacements for pre- and post-Milrow surveys. All data projected from road to line of section.

fault located about 1.3 km towards Y from GZ. The downthrown side of the fault is towards GZ. Horizontal strain data, from strain grid C' (figs. 12, 22), which crossed this fault northeast of where the level line crossed it, also suggest fault movement. The highly erratic nature of some elevations near GZ is probably the result of the survey stations being jostled slightly out of place by the very high accelerations they received from the nearby explosion.

Elevation changes in profile Z-Z' (fig. 11) appear to have smoother trends than changes in the other cross sections because the scale in Z-Z' is smaller than those of the other profiles. The most significant features of profile Z-Z' are: (1) the depression or sink which extends approximately 0.4 km each way from GZ, and (2) the lip southwest of GZ (at 0.45 km) is appreciably higher than the lip (at 0.5 km) northeast of GZ. The depression indicates that the stopping process above the explosion-formed cavity extended nearly to the surface. This is common for most contained underground nuclear explosions. The difference in elevation of the lip either side of GZ is indicative of asymmetrical doming.

Interpretation of the profiles will be incomplete until some of the highly erratic elevation changes of certain stations that depart from trends are either confirmed or explained. In profile W-W' (fig. 9), for example, the decrease in elevation approximately 1.3 km from point W may be significant. Also, the generally higher elevations from W' northwestward to a point 2 km from W' may also

Figure 11.--Profile Z-Z' showing GZ and vertical displacements from pre- and post-Milrow surveys. All data projected from road to line of section.

be significant. The apparent erratic elevations of some stations in these zones, however, leave any interpretations open to question.

Although some vertical displacement along faults is indicated by the level-line data, the amount of movement is much less than the movement measured across faults at similar distances from explosions of about 1 megaton in Pahute Mesa at the Nevada Test Site. The tectonic significance of these differences is not yet known.

Strain determinations

Strain was calculated from changes in distances determined by geodetic surveys of nine strain grids before and after the Milrow event. Six of these grids formed quadrilaterals labeled A through F (fig. 8) and were established and measured during the period September 4-12; they were remeasured after the Milrow event during the period October 21-27. Most of the survey stations of the quadrilaterals were copperweld rods driven to refusal through the turf and peat that covers most of this part of Amchitka; a few were copperweld rods set in bedrock, and a few were U.S. Corps of Engineers concrete monuments. One distance in each quadrilateral was measured with a laser-modified model 4 geodimeter. Angles between all points were measured with a Kern DKM-3 theodolite.

The three strain grids closest to the explosion, labeled A', B', and C' (fig. 12), form irregular geometric figures which were dependent upon available and suitable locations for stations. Stations consisted of pieces of concrete reinforcing rod driven to refusal or to a maximum of 1.5 m, whichever was less. All distances between

stations in nets A', B', and C' were measured with a model 6 geodimeter during the periods August 28-September 8, and October 8-14.

Principal strains were calculated from the changes in length of the sides of triangles that compose the quadrilaterals and the triangles that compose the irregular geometric figures of the nets closest to ground zero. The trilateration method of calculation described by Burford, Eaton, and Pakiser (1969) was used. As the accuracy of the model 6 geodimeter measurements probably is only about ± 1 cm, and the legs of the triangles range from about 0.2 km to a little more than 1.0 km, the precision of the measurements in terms of strain is less than 10^{-5} for grids A', B', and C'. For grids A, B, C, D, E, and F precision is about 10^{-5} or better for the calculated strains, owing to the somewhat greater accuracy of the model 4 geodimeter and the longer lines of the quadrilaterals.

The most obvious feature of the strains calculated from the quadrilaterals and shown on figures 13, 14, 15, and 16 is that strain grid C (fig. 8), which crosses the Constantine fault, has the largest strains and that these are all extensional. The next most obvious feature shown is that for all grids other than grid C, 9 out of 10 strains greater than 10^{-5} are extensional and oriented northeast-southwest. Extensional strains oriented in the same direction also occurred in grid C, but they do not appear to be the largest strains. The differences in strains that are oriented northeast-southwest or northwest-southeast in grid C are, however,

Figure 13-Map of part of Amchitka showing principal strains (arrows) and faults (heavy lines)

Figure 14.—Displacements and principal strains resulting from Milrow event (grids A&B)

Figure 15.— Displacements and principal strains resulting from
Milrow event (grids C & D)

EXPLANATION

—————
Probable fault

↔ 1×10^{-5} extension

↔ " compression

Principal strain axes

-5
-3.3

Pre- to postevent distance
change in millimeters. Upper
number as measured, lower
number corrected for cavity
emplacement

Figure 16. - Displacements and principal strains resulting from
Milrow event (grids E & F)

less than the precision (10^{-5}) of the data. The significance of strains less than 10^{-5} is not obvious, and possibly an interpretation of them is not valid. However, when a group of them with similar orientation and magnitude occurs in a small area, such as for quadrilateral F (the northwesternmost group of strain arrows on fig. 13), some credibility seems likely.

Preliminary conclusions based on the strain data calculated from surveys of the six quadrilaterals A through F are:

(1) A small amount of movement occurred either within or near quadrilateral C.

(2) The amount of strain with respect to distance from GZ appears to be less than strain determined at similar distances on Pahute Mesa at Nevada Test Site for explosions of about 1 megaton.

(3) The amount of strain on Amchitka is less than 10^{-5} at distances of about 10 km.

The three strain grids A', B', and C' (fig. 12) are near enough to GZ to require corrections to be made to the distances measured between stations. The correction is the displacement radial to GZ calculated according to a free-field method described by Essaglou and Rogich (1965). A 300-foot-radius (92 m) cavity was assumed for the calculations. The measured and corrected distance changes are shown in figures 17, 18, and 19. The principal strains calculated from the corrected distance changes are shown in figures 20, 21, and 22.

In grid A' (fig. 20) strains are generally largest across and on the northwest side of the Rifle Range fault. The subradial direction

FIGURE 17.-DISPLACEMENTS, MILROW EVENT, GRID A'

FIGURE 19.-DISPLACEMENTS, MILROW EVENT, GRID C'

EXPLANATION

- $\longleftrightarrow$ 1×10^{-4} extension
- $\nabla \nabla$ 1×10^{-4} compression
- Principal strain axes
- 12
Survey station

Figure 20.- Principal strains, grid A', Milrow event

Figure 22.- Principal strains, grid C', Milrow event

of some of the large compressional strains closest to ground zero suggests that the strains may be related to cavity growth. Interpretation of these strains, however, cannot be made with certainty because the stability of three stations--12, 13, and 2 (fig. 20)--is doubtful. Postexplosion examination of these stations indicated that they may have moved because of slump or spalling of the ground. Interpretation of the remainder of the grid unaffected by these stations is incomplete.

The principal strains calculated for the triangles that compose grid B' (fig. 21) indicate less effect from the explosion than from movement along the Rifle Range fault. The orientation of many of the largest compressional strains, for example, is not radial to ground zero. Further, lines that were shortened most are those that cross the Rifle Range fault. These lines are between stations 3 and 101, and between stations 4 and 92 (fig. 21). The change in distance between stations 3 and 101 seems particularly significant because very little change occurred on a continuation of this line toward station 7 and GZ.

The southeastern part of grid B' is slightly expanded, which can be interpreted as resulting from upward movement on the southeast side of the Rifle Range fault. Strains on the northwest side of the fault, therefore, should generally show compression parallel to the fault and extension normal to the fault. As the compressions are neither in the directions nor locations that were to be expected for simple

normal faulting, consideration of other data and more detailed analyses are needed before a satisfactory interpretation can be made.

Most of the principal strains in grid C' show large compressions in the direction of ground zero (fig. 22). The directions of compression diverge, however, closest to ground zero. Because of this divergence and because compressions in the directions shown on figure 22 are to be expected if downward movement on the southeast side of the fault as shown in this figure occurred, the strains may be interpreted as the result of fault movement. This interpretation is compatible with the level-line data, which also showed downward movement on the southeast side of the same fault (fig. 10).

Tilt determinations

Tilt was calculated from measurements of the relative changes in water level before and after the Milrow event at three rods in each of five lakes. The measurements are given in table 1. The locations of the lakes and calculated tilts are shown on figure 12. In effect, the lakes were used as long-baseline liquid-level tiltmeters. The distances between rods ranged from 82 to 335 meters (table 2a). Water level was measured from the top of each rod with a steel tape graduated in 0.01-foot (3 mm) intervals. The accuracy of all postshot measurements is better than 3 mm. The accuracy of preshot measurements, however, is somewhat variable from lake to lake and probably ranges from less than ± 0.01 foot (3 mm) to possibly as much as ± 0.05 foot (15 mm). In general the most inaccurate measurements were made

Table 1.--Preshot and postshot water levels (in centimeters)
below top of rod, and average relative difference
in water level.

Lake ^{1/}	Rod no.	Preshot water level	Postshot water level			Average relative difference ^{2/}
			Reading no.			
			1	2	3	
A	1	94.5	91.6	93.0	94.8	0.0
	2	90.2	87.2	88.5	90.5	<u>3/</u> -0.1
	3	100.3	98.5	100.0	101.7	+1.1
B	1	72.8	64.7	65.7	71.9	0.0
	2	42.1	35.5	36.6	42.5	+1.6
	3	36.0	36.6	37.8	43.6	+8.7
C	1	67.4	64.8	65.5	64.9	0.0
	2	40.2	39.0	39.5	39.2	+1.4
	3	61.6	65.5	66.3	65.5	+6.5
D	1	52.4	56.4	57.8	65.1	0.0
	2	57.6	60.2	61.7	68.7	-1.4
	3	40.2	43.6	45.1	52.1	-0.6
E	1	44.8	43.0	43.7	45.7	0.0
	2	50.3	48.8	49.5	51.2	0.0
	3	60.7	58.5	59.4	61.1	-0.4

^{1/} Locations of lakes A, B, C, D, and E are shown on figure 12.

^{2/} Water levels in the lakes fluctuated from natural causes during the interval of the postshot readings. To eliminate this variation, each set of postshot readings was adjusted by an amount sufficient to make the postshot Rod 1 values the same as the preshot Rod 1 values. The relative difference column is based on the average of these adjusted values.

^{3/} + indicates relative rise of lake bottom; - indicates relative drop of lake bottom.

Table 2a.--Distances (in meters) and bearings of lines between rods 1, 2, and 3

Lake	Line					
	1-2		2-3		3-1	
	Distance	Bearing	Distance	Bearing	Distance	Bearing
A	192	S.28°E.	174	N.76°W.	152	N.31°E.
B	326	S.83°E.	335	S.60°W.	210	N.09°W.
C	125	S.36°W.	189	N.46°W.	210	S.82°E.
D	162	S.18°W.	82	N.45°W.	140	N.48°E.
E	137	S.55°E.	192	S.41°W.	226	N.03°E.

Table 2b.--Direction and amount of tilt and distance from GZ

Lake	Direction of tilt	Amount of tilt (radians)	Distance from GZ (meters)
A	N.65°E.	8.8×10^{-5}	3,540
B	N.00°E.	4.2×10^{-4}	1,830
C	S.75°E.	3.1×10^{-4}	1,220
D	S.20°E.	1.1×10^{-4}	1,580
E	S.35°W.	2.1×10^{-5}	2,680

at lakes A and B. The levels and changes in levels given in table 1 have not been rounded off to conform to the estimated accuracy. In general, the least accurate measurements were made at lakes A and B. A clear plastic tube was placed over the rods to damp wave action during measurements. Accuracy of the postshot measurements is generally better than that of the preshot measurements because modification of the plastic tube system improved the wave damping.

The direction and amount of tilt at each lake was calculated using the conventional 3-point method. The results are given in table 2b and illustrated on figure 12.

Tilt determination at the three lakes B, C, and D (fig. 12) nearest to Milrow GZ, indicates tilting away from GZ, which is reasonable. The cause of the divergence of tilt direction at lakes A and E is not accounted for but may be related to motion on nearby faults. The amount of tilt at lake D is anomalously small compared with the tilt at lake B, which is about the same distance from ground zero as lake D. The amount of tilt at lake E is also anomalously small. These small values of tilt are believed to be due in part to presence of the Rifle Range fault between ground zero and the lakes D and E. Attenuation by the fault of displacement from cavity expansion, or perhaps movement on the fault, may have caused the anomalously small tilts. Horizontal strains measured in parts of grids A' and B' and in the vicinity of lakes D and E were also small and, therefore, compatible with the tilt data.

IV. STRESS DETERMINATIONS MADE ON AMCHITKA ISLAND BEFORE AND AFTER THE MILROW EVENT

By

T. C. Nichols, Jr., and F. T. Lee

Between September 10 and 22, 1969, four three-dimensional (3-D) stress probes were installed in drill holes on Amchitka Island at locations S1 through S4 (fig. 8) to monitor long-term strain changes in the rock mass. The probes, ancillary equipment, and procedures are described in detail by Lee, Nichols, and Abel (1969). The locations were chosen in the best possible rock outcrops near or adjacent to the U.S. Geological Survey's geodetic strain grids A, C, and D (fig. 8). The rock mass in these outcrops is highly fractured to a depth of at least 4.88 m, mostly as a result of mechanical weathering processes.

The stress probes were grouted in the bottom of the drilled holes at depths of 3.35-4.88 m, and the grout was allowed to set until the instruments stabilized. Stabilization took place in approximately 3 days, and thereafter measurements were made daily to detect changes of strain in the rock. Daily readings were made until October 5, 1969--D+3. No readings were made between October 5 and November 26.

Between November 26 and December 10, a USGS 3-D stress probe and a U.S. Bureau of Mines 3-component deformation probe were emplaced in a newly drilled hole at S4, and a USBM 3-component deformation probe was installed in two holes drilled at S5 (fig. 8). These

instruments were then overcored by USGS and U.S. Bureau of Mines personnel using standard methods described by Merrill (1967) to determine the natural state of stress of the near-surface rocks at these points.

In the new hole at site S4 one determination of the natural-state stresses in the horizontal plane was made with the USBM instrument at the 2.44 m-depth, and one determination of the natural-state stress tensor was made with the USGS instrument at 3.66 m. In the holes at S5, three more determinations of stress in the horizontal plane were made at the 0.30-, 0.46-, and 0.61-m depths with the USBM instrument.

Data obtained from the permanent 3-D stress probe installations at sites S1 through S3 were used to calculate stress changes before and after the Milrow event. Data from the permanent probe at S4 were not used because the instrument malfunctioned. During the period September 20-October 5, 1969, which included the Milrow event on October 2, no significant stress changes were recorded. Small recorded changes were within the limit of error of the instruments, except those changes (table 3) that occurred during the periods September 21-24 and October 1-2. Large and small changes were recorded, however, during the period October 5-December 10. These and selected significant values are shown in table 3 and figure 23.

Figure 23 is a Schmidt net, lower-hemisphere plot of the stress-change directions given in table 3. Also plotted are the Constantine fault plane (shown on fig. 8) and the range of trends of other major

Table 3.--Stress-change tensors during selected intervals
of time at three sites on Amchitka Island

Time period 9-19-69 to 12-09-69	Stress-probe site no. ^{1/}	Principal stress changes ^{2/} + values = compression - values = tension		Computed bearing and plunge of stress- change axes ^{4/}	
		(psi)	(kg/cm ²) ^{3/}		
9-19 to 11-27	S1	$\Delta\sigma_1$	397	27.9	N. 47.6° E. 51.0°
		$\Delta\sigma_2$	150	10.6	S. 7.5° E. 24.9°
		$\Delta\sigma_3$	100	7.0	N. 83.3° W. 28.0°
9-19 to 11-27	S2	$\Delta\sigma_1$	396	27.8	N. 58.9° E. 36.2°
		$\Delta\sigma_2$	78	5.5	S. 25.2° E. 7.5°
		$\Delta\sigma_3$	- 43	- 3.0	S. 76.2° W. 52.8°
9-21 to 9-24	S3	$\Delta\sigma_1$	- 51	- 3.6	N. 51.4° W. 44.3°
		$\Delta\sigma_2$	- 73	- 5.1	S. 10.1° E. 37.6°
		$\Delta\sigma_3$	-129	- 7.3	N. 61.8° E. 22.0°
9-21 to 11-27	S3	$\Delta\sigma_1$	- 64	- 4.5	N. 38.8° E. 28.8°
		$\Delta\sigma_2$	-310	-21.8	S. 47.3° W. 60.9°
		$\Delta\sigma_3$	-577	-40.6	S. 49.2° E. 3.6°
10-01 to 10-02	S3	$\Delta\sigma_1$	- 25	1.8	N. 30.6° E. 43.8°
		$\Delta\sigma_2$	- 61	- 4.3	S. 27.0° W. 46.1°
		$\Delta\sigma_3$	-106	- 7.5	N. 61.1° W. 1.8°
10-05 to 11-27	S1	$\Delta\sigma_1$	373	26.2	N. 51.7° E. 37.5°
		$\Delta\sigma_2$	136	9.6	S. 20.0° E. 22.2°
		$\Delta\sigma_3$	93	6.5	N. 86.7° W. 44.2°
10-05 to 11-27	S2	$\Delta\sigma_1$	426	30.0	N. 55.0° E. 32.5°
		$\Delta\sigma_2$	86	6.0	N. 34.5° W. 0.2°
		$\Delta\sigma_3$	- 6	- 0.4	S. 56.9° W. 57.5°
10-05 to 11-27	S3	$\Delta\sigma_1$	47	3.3	N. 41.2° E. 26.3°
		$\Delta\sigma_2$	-200	14.1	S. 41.1° W. 63.7°
		$\Delta\sigma_3$	-425	-29.9	N. 48.8° W. 0.1°
11-29 to 12-01	S2	$\Delta\sigma_1$	- 40	- 2.8	S. 32.3° W. 43.2°
		$\Delta\sigma_2$	- 59	- 4.1	N. 48.0° W. 11.5°
		$\Delta\sigma_3$	-153	-10.8	N. 52.2° E. 44.5°
12-07 to 12-09	S2	$\Delta\sigma_1$	160	11.2	N. 56.6° E. 48.5°
		$\Delta\sigma_2$	55	3.9	S. 31.9° E. 0.3°
		$\Delta\sigma_3$	13	0.9	S. 59.3° W. 41.4°

1/ Locations of stress-probe sites are shown on figure 8.

2/ Estimated instrument errors may produce deviations as much as ± 3.5 kg/cm².

3/ Conversion equation used for conversion to cgs system:
1 psi = .0703 kg/cm².

4/ Estimated instrument errors may affect determination of bearing and
plunge of principal stress axes about $\pm 6^\circ$.

Figure 23.--Equal-area diagram (lower hemisphere) showing selected principal stress change directions determined at sites S1, S2, and S3, and the natural-state stress directions determined at site S4. Also, major structural features are plotted. Stress directions from S1 are shown by ⊙, from S2 by ◻, from S3 by ⊗, and from the overcoring operation at S4 by ●. Numbers 1, 2, and 3 indicate respectively the major, intermediate, and minor principal stress changes.

faults on the island. It is of interest to note that the stress-change directions cluster close to the fault planes or close to their poles and thus appear to be related to the faults. Also, it is interesting to note the magnitudes of stress changes for the period October 5-November 27, 1969, at all sites (table 3). The instruments at sites S1 and S2 show very similar magnitudes of compressive stress change for $\Delta\sigma_1$ and slightly differing magnitudes of stress changes (mostly compressive) for $\Delta\sigma_2$ and $\Delta\sigma_3$; thus the changes of the stress field during this period appear to be quite similar at these two locations. This suggests that such superposed stress changes may have been applied somewhat uniformly over the surface-rock mass between S1 and S2. The instrument at site S3 showed mostly tensile changes, suggesting that the structural discontinuities between S3 to the north and S1 and S2 to the south are also stress discontinuities.

As no readings were taken between October 5 and November 27, it is impossible to know when during that interval the above stress changes took place and what magnitudes they may have attained. Whether or not the changes are related to Milrow is unknown; if they are related, there is a definite time lag involved.

The overcore data determinations of the natural state of stress are shown in table 4. From both types of instruments used, results showed a low-magnitude directional stress field with both compressive and tensile components. The natural-state principal-stress directions determined at S4 are plotted on figure 23 and appear to have no

Table 4.--Natural state of stress data from overcoring

A. Bureau of Mines three-component borehole deformation gauge-measurements made in horizontal plane

Site	Depth (feet)	P		Direction of P ^{3/}	Q		Direction of Q ^{3/}
		psi ^{1/}	kg/cm ² ^{2/}		psi ^{1/}	kg/cm ² ^{2/}	
S4	8	65	4.6	S. 67° E.	- 59	- 4.1	N. 23° E.
S5	1	1	0.0	S. 66° E.	-147	-10.3	N. 24° E.
S5	1.5	35	2.5	S. 84° E.	- 12	- 0.8	N. 6° E.
S5	2	27	1.9	S. 69° E.	- 90	- 6.3	N. 21° E.

B. U.S. Geological Survey 3-D stress probe. 3-D tensor at same location and depth

Stress magnitude			Bearing and plunge ^{3/}	
Component	psi ^{1/}	kg/cm ² ^{2/}		
σ ₁	43	3.0	N. 32° W.	53°
σ ₂	- 77	- 5.4	S. 85° E.	24°
σ ₃	-175	-12.3	S. 17° W.	26°

+ values = compression.

- values = tension.

^{1/} Estimated instrument errors may allow deviations as much as ± 3.5 kg/cm².

^{2/} Conversion equation used to convert to cgs system; 1 psi = .0703 kg/cm².

^{3/} Estimated instrument errors may affect determination of bearing and plunge of principal stress axes about $\pm 6^\circ$.

relation to the stress-change directions monitored at sites S1, S2, and S3.

Such a low-intensity directional stress field could be a reflection of a much more intense tectonic stress field at some depth where the rock is less fractured, or, possibly, it could be attributable to residual stresses locked into the rock. Perhaps there is some component of both.

V. HYDROLOGIC EFFECTS OF THE MILROW EVENT

By

W. C. Ballance and W. W. Dudley

Surface effects

The most obvious hydrologic effects of the Milrow event were those visible at land surface. Photographs taken from aircraft at the time of the event showed water geysers as far as 1,300 m from GZ. These were seen along streams, in lines across lakes, and along the beach on the Pacific side of the island. Evidence of mud geysers was also seen during on-site inspection of the area after the event. The dense turf and peat, which cover most of the area, might have restricted many potential geysers that otherwise might have occurred. The geysers, which were predicted, were probably caused by water that was forced under high pressure from fractures that closed during compression of the rock mass. These fractures generally are obscured by turf and lakes, but they can be seen in some stream channels and along the strand line, especially during low tide. The water discharged in geysers was derived from shallow depth near the points of discharge.

The ground surface at the Milrow GZ subsided about 6.1 m (20 ft). The subsidence was rectilinear and extended to a limit of about 270 m (875 ft) from GZ. Two lakes in the subsided area tilted toward GZ. The lake north of GZ drained to the west before the event, but it now discharges southward into the Milrow depression.

Clevenger Creek (fig. 8), the major surface-water drainage for the Milrow site, was affected considerably by sloughing of tundra from its steep banks, which partially filled the channel and restricted the stream flow.

Constantine Spring, about 4.4 kilometers southeast of GZ, is the domestic water supply for the base camp on the southeast end of Amchitka Island. The flow of the spring, which is derived from shallow local circulation of ground water, was temporarily affected by the hydraulic overpressure resulting from the event. The water from the spring, which is normally clear, was muddied with sediment for several days following the event.

Strain-gage transducers (Statham PM399TC) were installed in four streams on Amchitka prior to the event to record any changes in stream stage that might occur during and following the event. Clevenger Creek, the nearest stream that was instrumented (about 800 m south of the event site), had a base flow of about 3,800 m³pd (cubic meters per day) (1.55 cfs) prior to the event. About 15 minutes after the detonation, the discharge increased to a peak flow of 6,200 m³pd (2.55 cfs) and then decreased to an average of about 5,800 m³pd (2.40 cfs) for 3 hours following the event (fig. 24). The gage height then rose to about 50 cm above base flow, remained at this level for about 30 minutes, and then began a slow decline. Although the gage height increased, the discharge remained about the same--5,800 m³pd (2.40 cfs).

Figure 24.--Stream stages at Clevenger Creek gage and Constantine Spring gage after the Milrow event.

The first rise in gage height following detonation probably was caused by runoff of water that was squeezed from saturated peat and from fractures as a result of compaction of the rocks. The large secondary increase in gage height was caused by sloughing of the stream banks, which restricted the flow in the vicinity of the transducer and increased the gage height.

The discharge of Clevenger Creek was compared with that of Limpet Creek, which is near site F (fig. 1), to evaluate possible long-term changes in the discharge of Clevenger Creek. Limpet Creek showed a 99 percent increase in discharge during October, a 19 percent increase in discharge during November, and a 61 percent decrease during December 1969, as compared to the discharge for the same months of 1968. The Clevenger Creek drainage probably receives about the same amount of precipitation per unit area as the Limpet Creek drainage. However, the discharge of Clevenger Creek was 57 percent less during October, 63 percent less during November, and 83 percent less during December 1969, as compared with the discharge for the same months of 1968. This amounts to about $88,000 \text{ m}^3$ of water in October, about $83,000 \text{ m}^3$ in November, and about $24,000 \text{ m}^3$ of water in December 1969 that presumably was intercepted by the Milrow collapse depression and chimney. As additional stream-flow data become available, these estimates of water interception will be refined. Part of the intercepted water was from precipitation runoff and part was from ground water that normally would have been discharged to the creek. Inspection of the Milrow site in early March 1970, revealed that the tilted pond in the Milrow depression now captures surface runoff

from that portion of the preshot Clevenger Creek drainage that lies north of GZ. A substantial amount of water flows into this pond, but apparently no overflow to the south into Clevenger drainage has yet developed.

The instrumentation on Constantine Spring showed a slight instant rise and subsequent decline of gage height (fig. 24) moments after shot time, probably resulting from ground motion. The gage height returned to normal and after about 2 hours the gage height decreased about 5 cm and then gradually began to rise. The rise was probably caused by blocking of the spring flow at its exit or underground. This obstruction was gradually removed by the spring flow and the gage height returned to base flow.

Other streams instrumented with transducers were Bridge Creek and White Alice Creek. Bridge Creek was instrumented at the stream gage site near Infantry Road about 3.6 km north of site B (fig. 1). White Alice Creek was instrumented at the stream-gage site near the coast on the Bering Sea side of the island, about 8 km northwest of site B. Because of malfunction of the recorder chart drive at Bridge Creek no results were obtained. The transducer at White Alice Creek indicated a momentary rise of a few centimeters a few minutes after detonation. This probably was caused by some sloughing of the stream bank in the vicinity of the transducer.

Water samples taken in the vicinity of the Milrow site, before and after the event, showed no radionuclide contaminants. Water samples taken in the vicinity of the Long Shot site, about 2,500 m

(8,202 ft) north of the Milrow site, showed an increase in tritium after the Milrow event. This increase probably was due to mixing of water from effects evaluation hole 1, a test hole that was drilled about 4.6 m (15 ft) west of the Long Shot entry hole just before the Milrow event. Two zones in the effects evaluation hole yielded water containing low-level tritium from the Long Shot event. Water discharged from the hole during the testing drained into the area where the contaminated water samples were obtained.

Subsurface effects

Subsurface hydrologic effects resulting from the Milrow event presumably were: changes in water level in the chimney area, formation of a ground-water cone of depression around the chimney as ground water flows into the chimney, and mixing of radioactive contaminants with water in the chimney. These are the most significant hydrologic effects of the Milrow event because they involve the distribution of radioactive contaminants.

In the U.S. Geological Survey predictions, based on past experience at Nevada Test Site, it was assumed that the Milrow chimney would fill with water in 1 to 3 years. Later calculations, based on hydraulic properties of the rocks penetrated by the Milrow chimney, indicated that the chimney would fill by ground-water inflow in about 500 days and that interception of surface runoff by the collapse depression and subsequent chimney infiltration would increase the rate of chimney filling, shortening the time for chimney filling. The explanation of reduction in stream flow in the preceding

section (p. 53) shows that a significant quantity of water probably has been intercepted by the collapse depression and chimney.

Subsurface instrumentation and station locations

Three wells on Amchitka Island monitored hydraulic pressure responses during the Milrow event. They were UAe-1 at site C, UAe-6h at site D, and UAe-7h at site E (fig. 1). The water column was confined by an inflatable packer installed below the static water level in each well. Two strain-bridge pressure transducers, each activating separate recorders at the surface, were installed beneath the packers in each hole. Two purposes were served by the dual instrumentation. First, it was possible to run one recorder at a speed of 2.54 cm per second, providing good resolution for wave periods as short as 0.1 second, and the other at a speed of 0.25 cm per minute, providing continuous recording until the sites could be revisited after the explosion. Secondly, because all electronic components of the systems were separate, a malfunction of one system would not result in a complete loss of data.

All transducers installed in the Amchitka drill holes were Statham Models PA285TC. Placement and pressure ratings of these units are shown in table 5. The high-speed recorders at all sites were Bell and Howell CEC 5-126 oscillographs (CEC) fitted with model 7-315 galvanometers, rated for DC to 30 Hz response. For the slower, long-term recording, Esterline-Angus Speed-Servo S-2062 recorders (EA) were used. These are rated to follow full-scale signals up to a frequency of 4 Hz. Armored well-logging cable (0.8 cm diameter) was used to provide excitation power and to receive transducer signals and to support the inflatable packers.

Table 5.--Installation and pressure response data for wells on Amchitka Island, Milrow event

Site-----	C	D	E
Well number-----	UAe-1	UAe-6h	UAe-7h
Distance from GZ (km)-----	8.7	16.0	22.7
Direction from GZ-----	NW	NW	NW
Depth of well (m)-----	2,134.2	2,133.3	1,233.0
Static water depth (m)-----	35.1	29.0	45.7
Packer depth (m)-----	73.2	61.0	68.6
Transducer ratings (bars): CEC-----	172.0	34.5	6.9
do. EA-----	34.5	10.3	6.9
CEC response data:			
First arrival time (sec)-----	-	3.18	4.50
Maximum pressure (bars)-----	-	+5.9	+2.2
Arrival time (sec)-----	-	4.00	6.08
Minimum pressure (bars)-----	-	-3.6	-2.7
Arrival time (sec)-----	-	3.46	6.38
Observed periods ^{1/} (sec)-----	-	0.35*	0.60*
		0.31	0.20
		2.7	1.7
EA response data:			
Maximum pressure (bars)-----	+7.4	+3.7	+1.7
Minimum pressure (bars)-----	-4.3	-2.4	-1.7

^{1/} Listed in order of arrival. Period of waves causing maximum and minimum pressures are denoted by an asterisk (*).

One well at Fort Richardson, near Anchorage, was instrumented in a similar fashion. A 3.45-bar (absolute) Statham PA285TC transducer was installed beneath an inflatable packer and mated by logging cable to a Honeywell model 906C Visicorder.

All installations were calibrated as complete systems by lowering transducers into the water and recording the system response. The calibrations were verified by calculating responses through manufacturer's specifications for all components.

Results: Excellent records were obtained on all recorders except the high-speed unit at site C, which failed to operate at shot time. The first 30 seconds of response at sites D and E are shown on figures 25 and 26, respectively. Table 5 lists the data acquired from these and the slow-speed records.

Figure 25 shows that the maximum positive pressure response at site D, according to the high-speed record, was +5.9 bars at 4.00 seconds after the shot and was caused by a wave having a period of 0.35 second. The Esterline-Angus recorder, however, indicated only +3.7 bars. The preshot calibrations of both systems were verified when the transducers were pulled after the shot. A similar discrepancy was found in the records at site E. According to manufacturer's specifications, there should be no significant attenuation of signal or overshoot in either system for the observed wave periods, and the 30 percent difference remains unexplained.

An apparent residual pressure increase is shown on both figures 25 and 26 at +30 seconds postshot. However, each well returned to

Fluid-pressure (preshot datum), in bars

Figure 25. Confined fluid-pressure response in hole UAe-6h, Site D.

Fluid-pressure (preshot datum), in bars

Figure 26. Confined fluid-pressure response in hole UAe-7h, Site E.

its preshot pressure on both recording systems about 2 minutes after the detonation.

The positive pressure responses during the dynamic phase are plotted against distance from the Milrow site on figure 27. The regression line shown is based only on the Esterline-Angus records, as the CEC recorder at site C did not operate satisfactorily. The close-in overpressures resulting from Milrow are significantly greater than those from events of similar magnitudes monitored at the Nevada Test Site, although the regression with distance is greater for Milrow.

Traditionally, ground-water pressure response is thought to result from dilatations of the saturated rock mass during passage of the seismic wave train. If this is true, the distance-regression exponents, peak arrival times, and peak periods for pressure response should be the same as those for displacement measurements in the seismic studies. From data presented by Environmental Research Corporation, the predicted and observed distance exponents for Milrow seismic displacement were calculated to be -1.42 and -1.64, respectively. The -1.54 distance exponent for the fluid overpressure regression compares favorably with these. However, the distance exponents for peak velocity and acceleration were about the same, or -1.46 and -1.63, respectively. On the basis of arrival times and wave periods, the peak fluid pressures correlate most closely with peak vertical particle velocity rather than peak displacement, although the correlation is not sufficiently good to be considered

Figure 27.--Aquifer overpressures in response to the Milrow event compared with prediction for a 1-megaton event at the Nevada Test Site. W is device yield in kilotons.

conclusive. Secondary fluid-pressure peaks, with longer periods (fig. 25 and 26), correlate better with displacement measurements, although the data are too sparse to identify any directional component that might be dominant.

The slow-speed records were examined in detail to identify fluid-pressure events occurring after the dynamic-phase response. At site E, the generator ran erratically much of the time and, because of its effect on the recorder amplifier, resolution became about 0.5 bar. Within this limit, no pressure events were observed for 45 hours postshot, when the station was dismantled. At site D the pressure increased 0.1 bar between +5.5 and +6.5 hours. It remained at this level until measurements were discontinued at +45.5 hours.

At site C a uniform, steady trace was obtained until +34.63 hours, or 0844, October 4, GMT (Greenwich mean time); at this time a negative step of 0.7 bar was recorded, followed by an immediate but only partial recovery to -0.3 bar. This reading persisted without change until 1524, October 5, GMT, when a similar step of 0.2 bar occurred, followed by immediate partial recovery of about 0.1 bar. According to preliminary seismic data M. L. Merritt, Sandia Corp. (written commun., 1969), four seismic events in the vicinity of the Milrow site were detected between 0841 and 0848, October 4, GMT. The earlier pressure step probably corresponds to this seismicity and probably represents the major episode of the chimney collapse. Nothing was recorded in the seismic study that can be correlated with the later pressure step.

Float-type water-level recorders were installed in UAe-7h on October 5 and in UAe-1 and UAe-6h on October 6. The recorder was removed from UAe-1 on November 14, 1969, but those at the other two sites will remain in use indefinitely. No unusual variations in water levels occurred at these sites, although the natural fluctuations in UAe-1 and UAe-6h are sufficiently great to mask anomalies of less than about 0.3 m (1 foot).

At the Fort Richardson installation the resolution was about 0.05 bar. The oscillograph record shows no detectable response to the Milrow event. However, an observer detected very slight motion in the galvanometer just prior to the radio announcement that the seismograph at the Anchorage Westward Hotel was responding. Extrapolation of the regression line, which is defined for the stations on Amchitka, indicates that the positive response would be 0.002 bar at a distance of 2,200 km. This is about an order of magnitude below the system resolution.

VI. SUMMARY OF MARINE GEOPHYSICAL STUDIES FOR THE MILROW EVENT

By

Roland von Huene and W. J. Carr

Two marine geophysical surveys were made around Amchitka Island to help evaluate geological effects of the Milrow underground nuclear test. Because large tsunamis may be generated by slumping of unstable sediment or by movement along faults, and because both of these events might be triggered by a nuclear test, the objectives of the first survey were to delineate submarine faults and large bodies of unstable sediment. The pretest survey was made during September 24-30, 1969, and the posttest survey October 8-10; the two surveys covered more than 1,200 km of ship's track (fig. 28). Instruments used in the surveys included a continuous seismic reflection system, a precision fathometer, and a proton precession magnetometer. After trying three seismic reflection systems that operate in three different frequency domains, a spark source with receiving instruments that record between 200 and 1,000 cycles per second was selected as the primary instrument system. The ship was navigated by radar, or by Loran A when the ship was beyond radar range.

Interpretation of geophysical data

The pattern and character of faults and of sediment distribution differ markedly from the Pacific side to the Bering Sea side of Amchitka. On the Pacific side the sea floor slopes gently away from the island (fig. 28), and there is a scarcity of reflective layers,

Figure 28.--Amchitka Island and vicinity showing bathymetry and location of ship's tracks of seismic surveys.

indicating little sediment. On the slope are canyons that trend transverse to the Aleutian Arc axis. Their sharp asymmetric profiles, long linear traces, and general parallelism to faults on the island, as well as a similar sense (direction) of vertical displacement, indicate that these bathymetric features are caused by faults. Fault scarps were not detected on a proglacial erosional terrace at 100 m depth; thus, significant faulting presumably has not occurred since the terrace was beveled.

Southeast of the island, along the slopes of Amchitka Canyon, the sea floor drops off in a series of fault steps that trend parallel to faults on the island. The steps have ridges on their outside (seaward) edges behind which tilted and eroded sediments locally occur. On the landward side of the steps, the sediment dips toward the faults. The faults in Amchitka Canyon appear to have been more active than those along the Pacific slope because the former have a much greater displacement; they dropped an older erosion surface far below wave base, and also cut younger sediments trapped in basins.

Faults on the Bering Sea side of Amchitka trend parallel to the Aleutian Arc. At the edge of the insular platform is a steep escarpment (Rat Islands escarpment) about 170 km long with a maximum height of 1,460 m (fig. 28). The escarpment appears to generally postdate the Chitka Point Formation of Miocene age, but post-Miocene sedimentary rocks onlap the scarp and are only slightly deformed by faulting and folding. The thick sediments in Oglala Valley north of the escarpment are not seen on the insular platform, suggesting that deposits in the valley collected after much of the escarpment was formed.

Seaward extent of the Rifle Range fault

The submarine extension of the Rifle Range fault was given special attention in the surveys because it is the largest fault known on Amchitka and is within about 1,200 m of the Milrow site (fig. 28).

Some evidence of the northeastward extension of this fault is seen in the seismic records and submarine topography of the Bering Sea floor. The fault probably passes near the tip of Kirilof Point, but it appears to end near the Rat Islands Escarpment. A series of closely spaced records on the Pacific side of Amchitka shows that the sea-floor expression of the Rifle Range fault ends about 5 km from shore; magnetic expression of the fault may extend another kilometer seaward. A double negative magnetic anomaly occurs over the fault; this, together with the configuration of the sea floor, suggests a fault zone locally as much as 500 m across. Submarine topographic expression of the Rifle Range fault terminates about 5 fathoms above the inner edge of the 100-meter-terrace level. This relatively young terrace apparently is not displaced by the fault. Furthermore, the aeromagnetic data (G. D. Bath, W. J. Carr, L. M. Gard, Jr., and W. D. Quinlivan, unpub. rept., 1969) do not indicate a continuation of the fault seaward.

After the Milrow event, some traverses across the Rifle Range fault were repeated. Where the scarp was 28 m high in the fathometer record prior to the test, it appeared 30 m high in the postshot record. The limitations of navigational accuracy and the irregularity of the scarp make it uncertain that the repeated record indicates movement of the fault as a result of Milrow.

The Aleutian Terrace and the Aleutian Trench

The steep slope between Amchitka Island and the Aleutian Trench is broken, about half way down, by the Aleutian Terrace. The only significant amount of sediment along the Pacific flank of the Aleutian ridge was noted along this terrace. Sediment on the inner parts of the terrace is tilted gently toward the trench, but otherwise stratification appears nearly horizontal. From a single record across the terrace it is not possible to determine whether or not a large thrust fault emerges at the terrace.

Two records of good quality were made across the Aleutian Trench. Horizontal sediment as much as 1.5 km thick partially fills the trench. The acoustic basement can be followed to the trench axis and it may continue under the insular wall of the trench. The records also suggest that the northern trench wall consists partly of tightly folded sediments, possibly caused by underthrusting.

Conclusions

Seismic studies confirm that the insular ridge around Amchitka is now relatively stable structurally, except in Amchitka Canyon where recent faulting probably has occurred. Large thrust faults that emerge at the Aleutian Terrace or at the Aleutian Trench, as suggested by seismological evidence, cannot be substantiated or disproved by the few geophysical data available, but these data indicate that a more extensive survey of the trench and terrace would show geologic structures significant to an understanding of the thrust fault problem.

The possibility of causing large submarine slumps by an underground nuclear explosion seems fairly unlikely from the data at hand. Apparently very little sediment has been deposited adjacent to Amchitka; but, farther from the island to the south, sediments are present on the Aleutian Terrace, and to the north they are trapped in Oglala Valley. Sedimentary rocks are also present in Ward Basin and other areas in and near Amchitka Canyon. The marine seismic work done for the Milrow event has shown the usefulness of this method in delineating areas of sedimentary rocks and the structures affecting them. Further work in critical locations could add more valuable information about the basins and valleys adjacent to Amchitka.

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