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US Army Corps
of Engineers
Los Angeles District

COAST OF CALIFORNIA
STORM AND TIDAL WAVES STUDY

COASTAL CLIFF SEDIMENTS
SAN DIEGO REGION (1887-1947)

CCSTWS 88-8
DECEMBER 1988

COASTAL CLIFF SEDIMENTS
SAN DIEGO REGION, DANA POINT TO THE MEXICAN BORDER (1887 to 1947)

Ref. No CCSTWS 88-8

Processes, Locations and Rates of Coastal Cliff Erosion from 1887 to 1947, Dana Point to the Mexican Border

Coast of California Storm and Tidal Waves Study

U.S. Army Corps of Engineers
Los Angeles District, Planning Division
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prepared by

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SUMMARY

An understanding of the location, frequency, grain size, mechanisms and volume of sea-cliff erosion is essential to the identification of coarse-grained littoral sediment sources and the quantification of sediment budgets in associated littoral sediment dispersal systems. Examination of coastal cliff and bluff changes in southern Orange and San Diego Counties from 1887 to 1947 (this report) and from 1947 to 1986 (Kuhn and others, 1987) by means of 1:24,000 and larger scale topographic maps as well as aerial and ground photographs indicates the importance of subaerial erosion in the production of coarse-grained sediment for the littoral zone. These studies document the temporally episodic and areally site-specific character of such erosion, which is shown to be directly related to prevailing meteorologic conditions.

From 1889 to 1968, minimum volumes of 14.285, 9.333 and 4.368 million cubic yards of coarse-grained sediment was delivered to the coastline through the dominantly subaerial erosion of sea cliffs and bluffs at San Onofre, Camp Pendleton and Torrey Pines, respectively. These values sum to a total of 27.986 million cubic yards. Even higher rates of erosion may have occurred during the more stormy periods of the 19th century.

Examination of the mineralogic content of the coastal cliffs and bluffs from San Onofre to Torrey Pines indicates the occurrence of a major petrofacies boundary between San Onofre and Camp Pendleton. The position of this boundary should provide insight concerning the amount and direction of net longshore transport in this region. Likewise, the localized occurrence of several other minerals may provide similar information when synthesized with mineralogic data from the littoral zone.

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I. INTRODUCTION

Objectives

1.1 The primary purpose of this report is to perform an semi-quantitative analysis of cliff erosion along the California coast from Dana Point to the Mexican Border (Figure 1) during the period from 1887 to 1947. Man-related changes and the impact of urbanization are illustrated on appropriate vertical or oblique aerial photographs, ground photographs and graphs. Such photographs are annotated to show the extent of the unique coastal change.

Purpose and Scope

1.2 The purpose of the Coast of California Storm and Tidal Waves Study is to collect, reduce and interpret oceanographic, meteorologic, hydrologic, geologic and sedimentologic information. Task 6 includes the collection, analysis and interpretation of sedimentologic data from the littoral zone. Results of Task 1D will be integrated with Task 9, River Sediment Discharge Study Task 8, River Sediments, and Task 7, Bluff Sediment Study to locate ultimate and local source areas and to determine the volumetric contribution of each potential source area to each beach segment.

Authority

1.3 This storm and tidal wave study is being undertaken pursuant to Section 208, of the Flood Control Act of 1965, Public Law 89-298.

Report Preparation

1.4 This report was prepared by Brian A. Robinson & Associates, Inc. under contract DACW09-87-R-0003. The scientists who wrote this report are Gerald G. Kuhn, Scripps Institution of Oceanography; and Robert H. Osborne, Eleanor A. Compton, and Tim Fogarty of the University of Southern California.

1.5 The study was initially funded by the House Appropriation Committee in its Report No. 97-177, 97th Congress, 1st Session (page 23). The Corps of Engineers has been directed to concentrate on the Dana Point to Mexican border segment of the study (House Report No. 97-177, page 23).

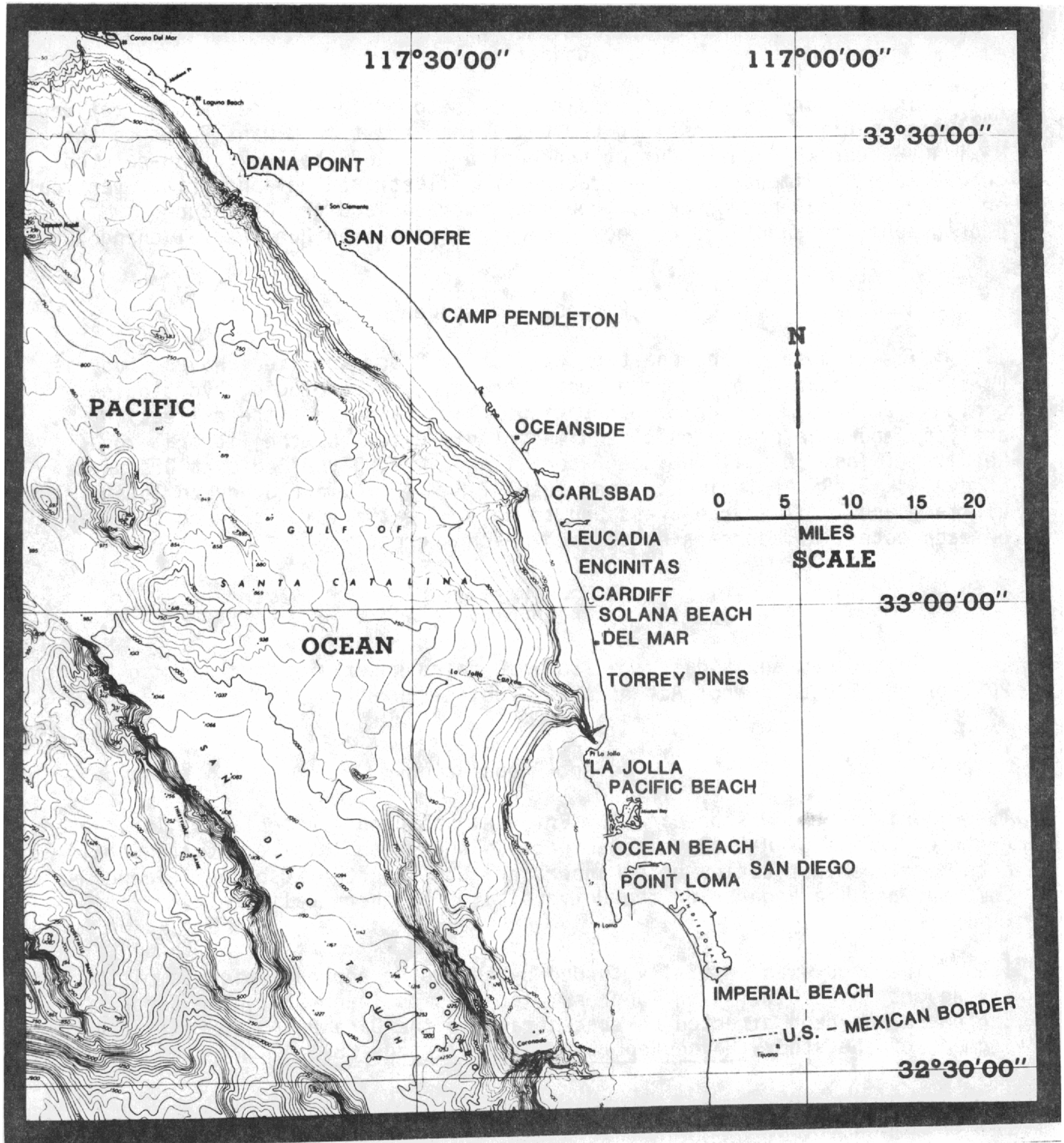


Figure 1. Location map of study area (from Kuhn and Shepard, 1984).

Prior Reports

1.6 The following are related reports prepared by the Los Angeles District which contain significant data on littoral zone sediments.

Title	Date
Beach Erosion Control Reports on Cooperative Study of Orange County, California. Appendix V, Phase 1.	June, 1959
Beach Erosion Control Report on Cooperative Study of San Diego County, California, Appendix IV, Phase 2.	March, 1960
Beach Erosion Control Report Cooperative Research and Data Collection Program of Southern California, Cape San Martin to Mexican Boundary. Three Year Report 1964-1966.	March, 1969
Three Year Report, 1967-1969 Cooperative Research and Data Collection Program, Coast of California.	December, 1970
Geomorphic Framework Report, Dana Point to the Mexican Border, Coast of California Storm and Tidal Waves Study.	September, 1984
Sediment Sampling, Dana Point to the Mexican Border (Task 1D, Nov-83 to Jan-84) CCSTWS 84-5.	November, 1984
Littoral Zone Sediments, San Diego Region, October 1983-June 1984. CCSTWS 85-11.	December, 1985
Coastal Cliff Sediments, San Diego Region, CCSTWS 87-2.	June, 1987

1.7 The methodologies employed in this report principally address three topics: (1) a historical review of climatic fluctuations and coastal erosion from the 1850's to 1947, (2) an estimate of the volume of sediment derived by subaerial erosion in the San Onofre, Camp Pendleton and Torrey Pines regions from 1889 to 1968; and (3) a description of the mineralogical associations (petrofacies) present in the sea cliffs and bluffs in the San Onofre, Camp Pendleton and Torrey Pines area.

1.8 The review of historic climatic fluctuations and coastal erosion is included to document the episodic and site-specific character of major storms and associated sediment yields from rivers and sea cliffs. Such information is essential to accurate numerical modelling and the computation of sediment budgets. The methodology used for such analyses is discussed thoroughly by Kuhn (1981).

1.9 The methodology used to estimate the volume of sediment derived by the subaerial erosion of sea cliffs and bluffs is presented in Chapter 7. The 1:10,000 scale maps prepared by the U.S. Coast and Geodetic Survey in 1889 were used as baselines, because of their scale and the fact that these represent the first systematic topographic survey in the San Diego region. The U.S. Geological Survey 7.5-minute series maps published in 1968 represent the most detailed recent maps that cover the entire study area. The 1:24,000 scale maps may show a potential conservative error as much as 80 feet (Fulton, 1981, p. 24). Thus the 1:24,000 scale maps only may be used to determine relatively large changes along the coastline. In fact, coastal cliff retreat in excess of 50 feet could barely be determined at this scale. Maps made to a scale larger than 1:24,000 usually cover restricted segments of the coastline, and often are not available for public usage. The 1:24,000 scale maps included in this report (PLates 1 through 6) have been augmented with numerous ground and aerial photographs to document the episodic and site-specific nature of subaerial sea cliff and bluff erosion.

1.10 Grain-size data used in the estimation of sediment yields from the sea cliffs and bluffs were supplied by the U.S. Army Corps of Engineers. The Wentworth grade scale is used in this report, and the numerical values for weight percent of sediment passing thorough a given sieve suplied by the U.S. Army Corps of Engineers were recomputed to the weight percent of sediment retained on a given sieve. The conventional moment measures (mean, standard deviation, skewness and kurtosis) were computed using the phi scale.

1.11 Thirty stratigraphic sections were measured along the coastal cliffs and bluffs in the San Onofre, Camp Pendleton and Torrey Pines areas. The Southern Pacific Laboratory of the U.S. Army Corps of Engineers performed mineralogic analyses on 69 samples selected from 16 of the stratigraphic sections measured. The purpose of this work is to identify the stratigraphic and geographic locations of distinctive minerals or mineral suites that might be used to identify sediment sources and transport pathways along the adjacent beaches. The detailed methodology is presented in Chapter 8.

2. SUMMARY OF REGIONAL GEOMORPHOLOGY

2.1 The eighty-one mile segment of the southern California coastline, from Dana Point to the U.S. - Mexico International Border, is located along the edge of the Santa Ana block (Wood and Elliott, 1979) of the Peninsular Range Geomorphic Province (Figure 2). Three major littoral cells have been recognized along this part of the coastline: the Oceanside, Mission Beach, and the Silver Strand cells (Emergy, 1960; Inman and Chamberlain, 1960). For more detailed description and locations, refer to the U.S. Army Corps of Engineers Report #CCSTWS 84-4, 1984. Plates 1 through 6 show the geology of the study area as well as the location of many of the figures. In addition, Plate 2 shows the location of the stratigraphic sections from which cliff sediment samples were collected in the San Onofre and Camp Pendleton areas, and Plate 4 shows the same type of information for the Torrey Pines area.

2.2 The Peninsular Range Geomorphic Province contains a series of large crustal blocks that have been uplifted and tilted to the west, forming plateaus (Jahns, 1954). The seaward edge of the plateau in the study area is assigned to the Santa Ana block. The major features of the Santa Ana block are: (1) a coastal plain from 1 to 5 miles wide along the western flank of the block, and (2) a coastal mountain range from 1,500 to 2,500 feet high along the eastern flank of the block (Figure 2). Underlying the surface of the coastal plain is a westward-thickening wedge of Mesozoic and Tertiary age conglomerate, sandstone and shale, which is capped by Quaternary non-marine and marine terrace and alluvial fan deposits. The coastal foothills and mountains consist of Mesozoic-age metamorphic and acid-plutonic crystalline "basement" rocks. (See U.S. Army Corps of Engineers Report #CCSTWS 84-4 plate 8 for regional geologic sections and general lithology.) At lower elevations, the coastal plain is modified by as many as 11 wave-cut terraces, which typically occur along the coast of southern California (Emery, 1960). Almost 72 miles of the approximately 81 miles of the coastline consist of narrow sandy beaches backed by bluffs and sea cliffs from 10 t0 400 feet high. The remainder of the coastline consists of either "drowned" valleys or sandy spits, such as Mission Beach or Silver Strand Beach.

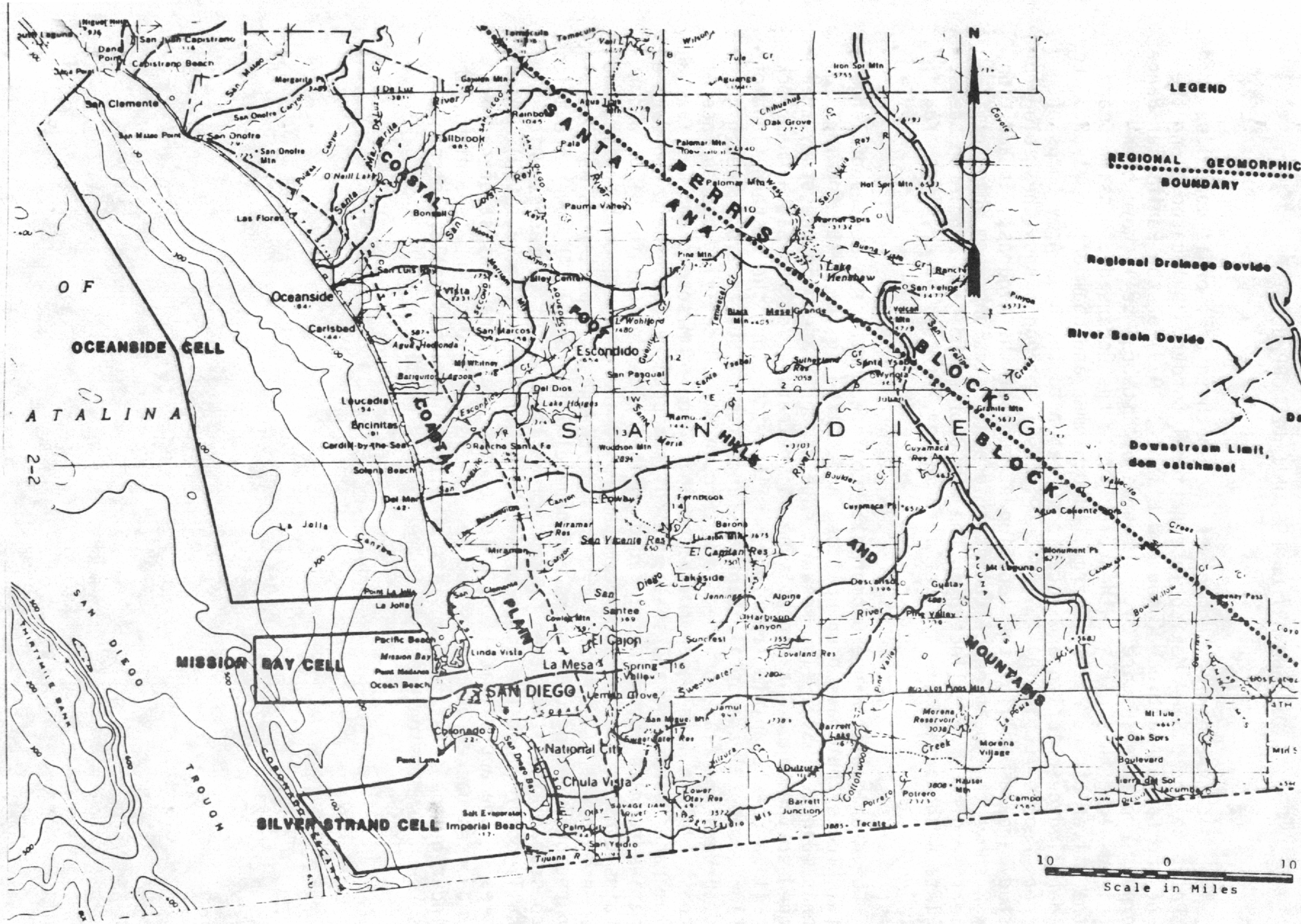


Figure 2. Regional geomorphology and littoral cells (from Army Corps of Engineers Report #CCSTWS 84-4).

3. COASTAL GEOLOGY

Exposed Strata

3.1 The sea cliffs from Dana Point to the United States-Mexico Border consist of unlithified sand to moderately well-indurated sandstone and conglomerate units, which range in age from late Cretaceous to Holocene (Figure 3). These strata are gently folded and are underlain by Mesozoic acid-plutonic rocks. The most abundant rock exposed in the cliffs are of marine and lagoonal origin, and are assigned to the La Jolla Group (Eocene). These strata crop out along the cliffs near Scripps Institution of Oceanography, La Jolla, and extend northward to Oceanside. These cliffs consist of siltstone, sandstone, and conglomerate. Locally, the cliffs are capped by late Pleistocene to Holocene alluvium.

3.2 Sandstone and siltstone units chiefly assigned to the Monterey Formation (Miocene) and some to the Capistrano Formation (late Miocene and Pliocene) are present in the coastal cliffs north of Oceanside (Young, 1980). Most of the cliffs are capped by variable thicknesses of marine or non-marine terrace and alluvial fan deposits of Quaternary age.

3.3 Generally, the oldest strata exposed in the cliffs occur at Point Loma, and successively younger strata crop out in cliff faces to the north. At San Clemente, the cliffs consist almost entirely of Quaternary sediment.

Cretaceous Strata

3.4 The Point Loma Formation, which is assigned to the late Cretaceous Rosario Group, crops out in the sea cliffs from Point Loma to La Jolla Shores Beach (Kennedy, 1975). The Point Loma Formation is more resistant to erosion than Eocene rock units and forms nearly vertical cliffs from 50 to 100 high. Descriptions of the Cretaceous Formations that crop out along the cliffed shoreline from La Jolla to Point Loma are given by Nilsen and Abbott (1979).

Eocene Strata

3.5 The strata assigned to the La Jolla Group were deposited in a submarine canyon and fan complex (Howell and Link, 1979) and range widely in sediment texture from deep-marine siltstone to coarse-grained, continental sandstone and conglomerate. The following formations, assigned to the La Jolla Group (Kennedy and Moore, 1971) are listed from oldest to youngest in geologic age: (1) Soledad Formation, (2) Del Mar Formation, (3) Torrey Sandstone, (4) Ardath Shale, (5) Scripps Formation, and (6) Friars Formation. These formations represent an emergent coastline sequence, and are dominantly sandstone and conglomerate. The Ardath Shale is the only unit assigned to the La Jolla

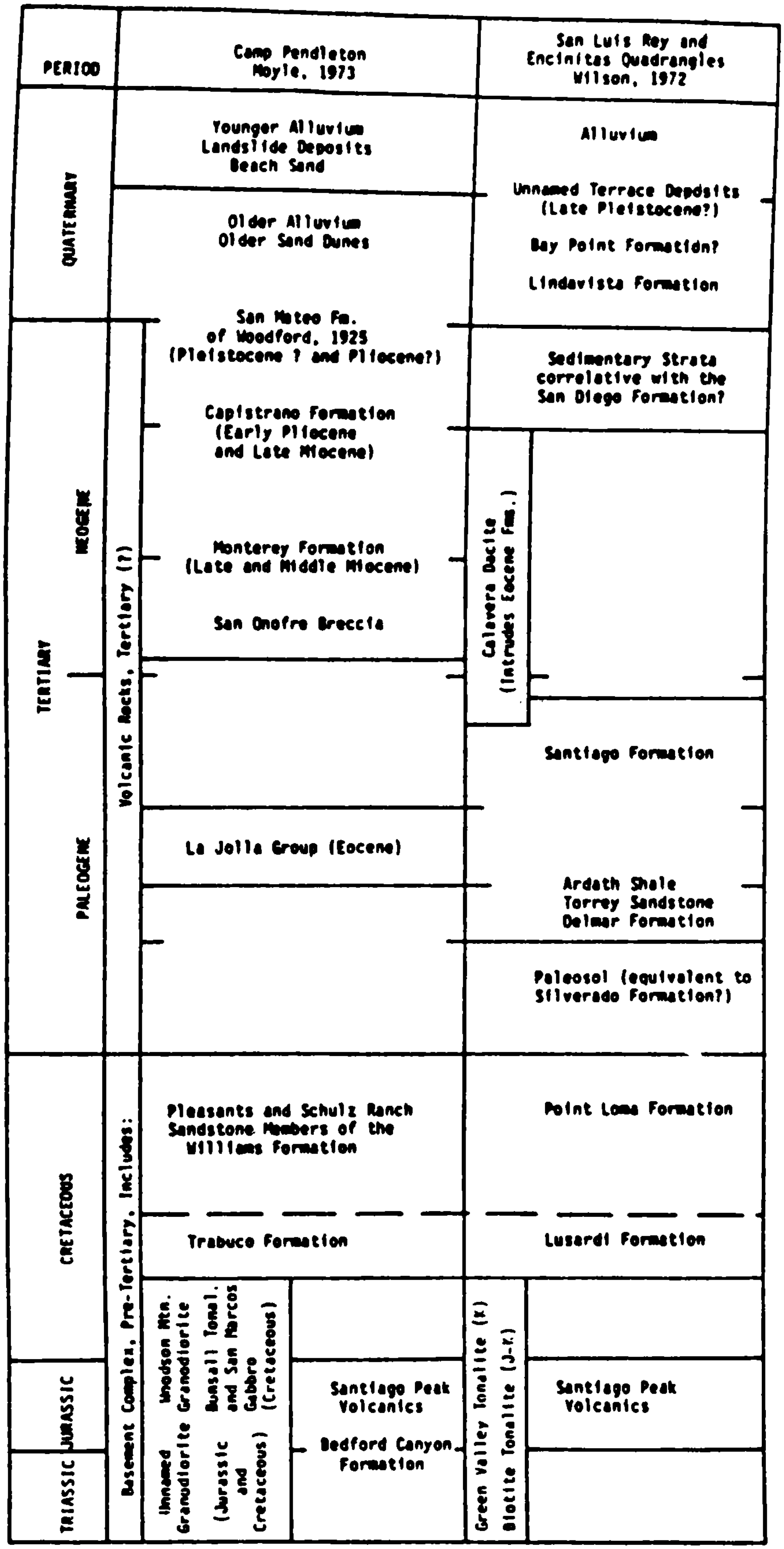


Figure 3. Stratigraphic correlation chart for western San Diego County and southern Orange County (from Elliott, 1975).

Group that contains very little sand. It is exposed along the sea cliffs from the Scripps pier to Torrey Pines State Park. Abundant microfossils indicate a deep-water marine faunal assemblage of middle Eocene Age (Bukry and Kennedy, 1969). The Ardath Shale is underlain by the Torrey Sandstone and overlain by the conglomeratic Scripps Formation. The Del Mar Formation is exposed near the town of Del Mar, and is overlain gradationally by the Torrey Sandstone. The Del Mar Formation consists mostly of yellowish-green sandy claystone, interbedded with grayish, coarse-grained sandstone. Brackish-water mollusks, almost entirely *Ostrea idriaensis*, suggest a lagoonal origin. Boyer and Warme (1975), provide detailed, site-specific descriptions of the Del Mar and Torrey Sandstone Formations.

Miocene Strate

3.6 The Monterey Formation (middle Miocene) crops out extensively along the beach from Oceanside Harbor to San Onofre. This formation is composed of an sandy facies with isolated resedimented deposits of the underlying San Onofre Breccia (Miocene) and a clayey siltstone facies (Ehlig, 1979). Strata also exposed in this area may be assigned to the Capistrano Formation (late Miocene and Pliocene), which includes both the typical diatomaceous, clayey-siltstone units and the arkosic sandstone of the San Mateo Member (Ehlig, 1979). Because the Capistrano and Monterey Formations are so similar in lithology, depositional environment, and stratigraphic position, it is difficult to distinguish these formations in the Camp Pendleton area (Young, 1980). In the area from directly north of the Santa Margarita River to the Cristianitos fault, the dominant, basal, sandy lithologies are assigned to the Monterey Formation; only minor outcrops of the Capistrano Formation are present. Both formations are unconformably overlain by Quaternary sediment in this area.

Pliocene Strata

3.7 Marine siltstone and sandstone facies of the Capistrano Formation (late Miocene and Pliocene) crop out extensively in the sea cliffs northwest of the Cristianitos fault to the Dana Point Harbor (Ehlig, 1979). Inasmuch as the coarse-grained, arkosic sandstone of the San Mateo interfingers with the thick siltstone of the Capistrano Formation west of the San Mateo Canyon, this sandy facies was renamed the San Mateo Member (Ehlig, 1979), as opposed to the San Mateo Formation (Woodford, 1925). The San Mateo Member correlates with a similar sandstone named the Oso Member (Vedder and others, 1957) that was deposited in the northern part of a structural trough that existed during the late Miocene and early Pliocene, known as the Capistrano Embayment. Much of these Pliocene strata occur north of Dana Point. They extend northward from the west side of the Cristianitos fault, which crosses the coastline approximately one mile south of the Nuclear Generating Station at San Onofre. Additionally, some of the nonmarine and marine terrace deposits are dated as late Pliocene by Vedder (1960).

3.8 The Capistrano Formation was originally deposited as a series of submarine landslides (Hess, 1979) that deposited sand and clay into a deep, trough-like basin during the late Miocene. Very thick deposits of weakly-cemented sandstone exposed in the cliff face represent channels in these submarine landslide deposits (Hess, 1979). Cliffs developed in the Capistrano Formation are very steep, and are incised by vertical bluff-face gullies. Due to the presence of rock rip-rap between the railroad right-of-way and the shoreline, most of the sand-size sediment is not delivered to the littoral zone. Hess (1979) has published descriptions of selected strtigraphic sections showing grain-size characteristics of the cliff exposures of the Capistrano Formation.

Pleistocene Strata

3.9 Most of the Pleistocene strata represented in the sea cliffs are unnamed marine or nonmarine terrace deposits, which form an uplifted emergent sequence as the eustatic high-standing sea levels fell (Ehlig, 1979). Very thick Pleistocene terrace deposits crop out north of Las Pulgas Canyon. Reddish-brown siltstone units contain interspersed conglomerate lenses and layers that are composed of blueschist and greenschist metamorphic clasts. In the southern half of the area from Dana Point to the U.S. - Mexico Border, the Bay Point Formation is widespread, and is best exposed along the sea cliffs. The Bay Point Formation consists of both marine and non-marine strata, which occur as poorly-consolidated, friable, brown, sandy-siltstone that caps the sea cliffs from Point Loma to Oceanside. These strata are easily eroded. South of Carlsbad to Batiquitos Lagoon, strata assigned to the Bay Point Formation and Holocene surficial deposits constitute most of the sea cliff faces.

4. COASTAL EROSION

Introduction

4.1 In a time frame from tens to hundreds of years, the erosion of sea cliffs, bluffs and canyon heads is temporally episodic, areally site-specific, and directly related to prevailing meteorological conditions (Kuhn and Shepard, 1984; Osborne and others, 1985). An understanding of the character of sea-cliff erosion is essential to the identification of littoral sand sources, and the quantification of sediment budgets in associated littoral and nearshore dispersal systems (Osborne and Pipkin, 1983; U. S. Army Corps of Engineers, 1984).

Classification of Coastal Cliffs

4.2 The San Diego County shoreline is about two-thirds cliff and one-third embayed or backed by coastal plains. Generally the cliffs are from 25 to 100 feet high, but a short segment of cliffs greater than 300 feet high occurs in the Torrey Pines area. The cliffs in the study area are indicated in Figure 4. Topographic profiles largely are determined by the dominant erosive process forming the cliffs and the erosive resistance and stratigraphic position of contained rock or sediment (Emery and Kuhn, 1982).

4.3 As indicated by Emery and Kuhn (1982), sea cliffs undergo three main stages: (1) ACTIVE --cliffs that consist of bedrock exposed by their continuous retreat under the influence of both marine and subaerial agents and processes; (2) INACTIVE --cliffs that are mantled, especially along their bases, by a cover of talus having slopes from 25 degrees to 30 degrees and commonly supporting land vegetation, including trees; and (3) FORMER --cliffs that have been removed from the influences of marine processes so that subaerial erosion rounds the crests and provides material for stream deposition beyond the bases (Figure 5). Examples of such former sea cliffs occur at San Juan Capistrano and San Clemente where coastal cliffs are now separated from the beach by a rock-protected railroad right-of-way.

4.4 Profiles of active sea cliffs appear to be controlled by two major agents; namely, marine and subaerial erosion.

Marine Erosion

4.5 Marine erosion is accomplished at the base of the sea cliffs by abrasion, biological activity, solution by ocean water and quarrying of blocks. Abrasion is materially increased by sediment (mainly sand and pebbles) carried in suspension. Relatively fast marine erosion produces oversteepening of the lower part of the cliffs (even undercutting or notching, as is common in limestone) that leads to rock falls, slumps and other kinds of mass movements (Emery and Kuhn, 1982).

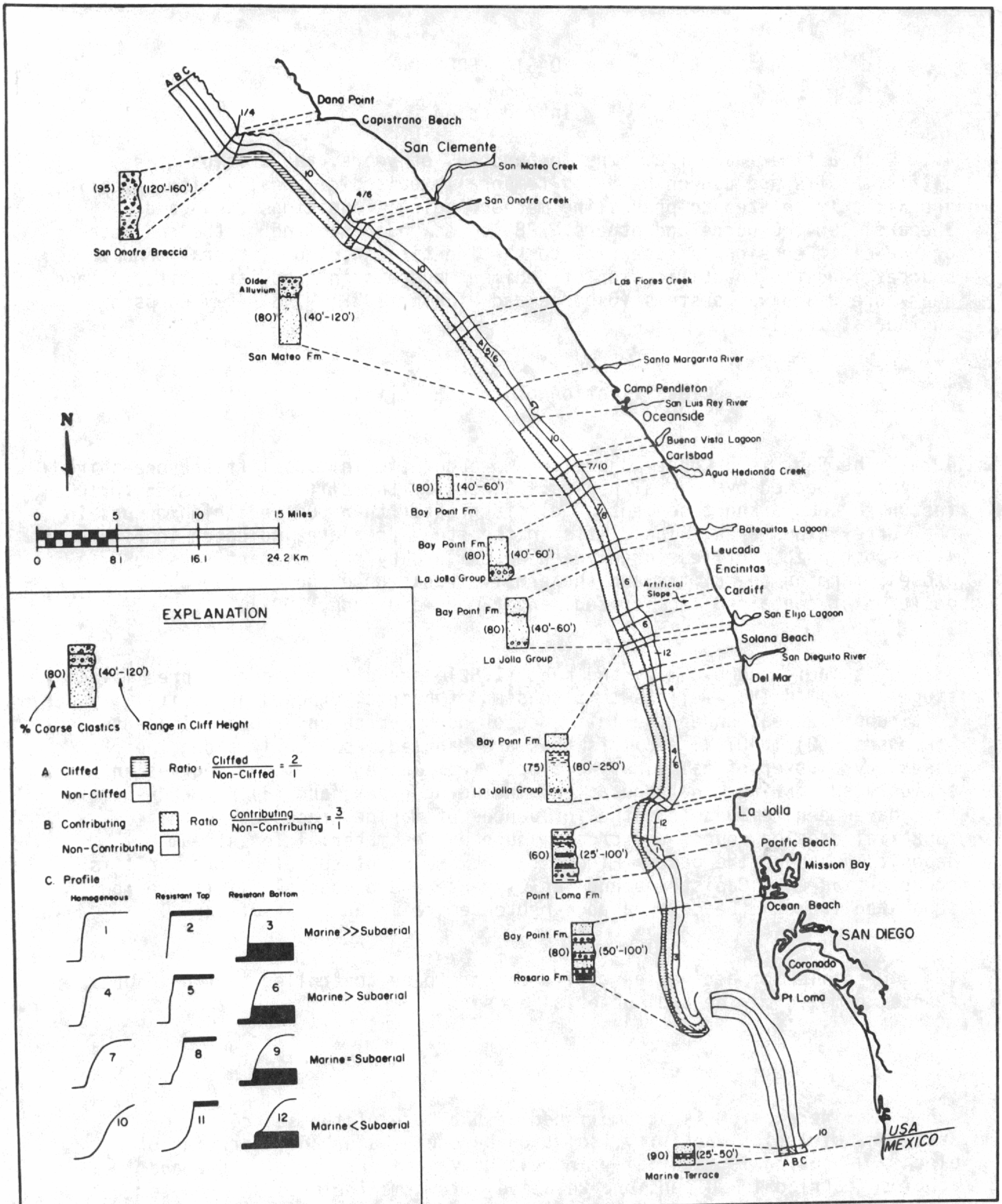


Figure 4. Classification of coastal cliffs (from Osborne and Pipkin (1983) and Army Corps of Engineers Report #CCSTWS 84-4; adapted from Emery and Kuhn, 1982).

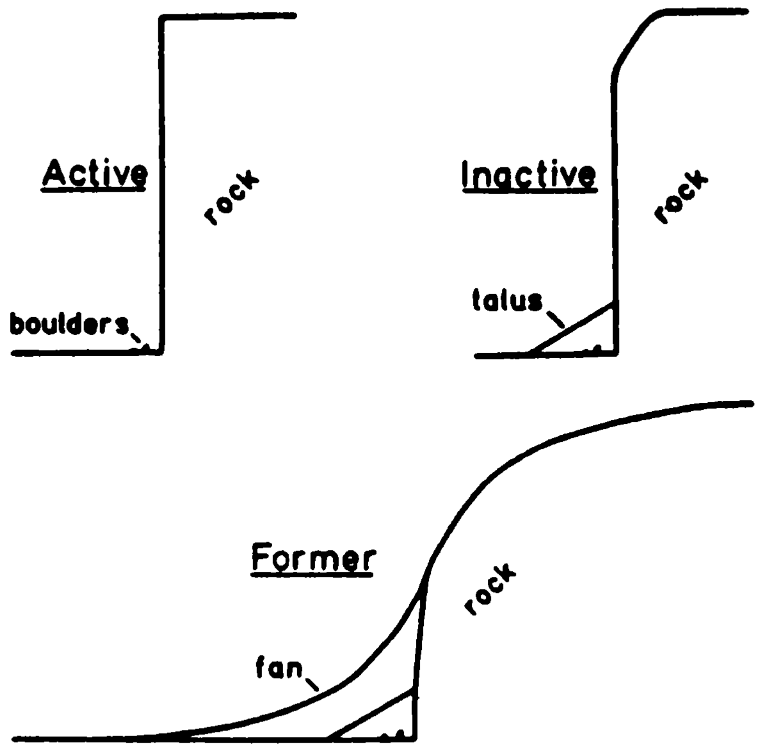


Figure 5. Idealized stages in geological history of a sea cliff (from Emery and Kuhn, 1982).

Subaerial Erosion

4.6 Subaerial erosion takes the form of gullying and rainwash at the ground surface and of slumping induced by ground water that weights, produces over-burden pressure, and causes clay minerals to expand. The wetted clay layers may represent highly lubricated layers, which may serve as planes of slip for a landslide. Where subaerial processes are dominant, the associated cliffs are mantled with colluvium and characteristically have talus or alluvial cones at their bases.

Impact of Urbanization

4.7 Construction by man has increased erosion by both marine and subaerial processes. Damming of rivers has reduced the contribution of sediment to the ocean, narrowing beaches and increasing wave erosion of sea cliffs. Erosion has been counterbalanced partly by local construction of sea walls and riprap barriers. Home construction atop the cliffs and on their faces also has increased subaerial erosion through construction of storm drains, fences, and stairways; removal of ground cover; oversteepening; overloading; and both accidental and purposeful release of water along the cliff face and into the bluff itself. Only partial compensation can be achieved by local provision of drains and gutters; in fact, many examples are known of actual increased local erosion caused by such protective measures (Emery and Kuhn, 1982).

4.8 In this study, as in the Corps of Engineers Geomorphology Framework Report in 1984, sea cliffs are classified according to the 12 cliff-profile types described by Emery and Kuhn (1982). These are illustrated in the explanation and strip map of Figure 4. Contributing and non-contributing cliffs are shown on the same figure. Non-contributing cliffs are mostly a product of man-induced activities, such as the construction of coastal protective structures or beach restoration and nourishment. For example, the non-contributing cliffs from San Clemente to Capistrano Beach reflect cliff separation from the beach by a highway or railroad embankment; and the non-contributing cliffs at Oceanside are covered by dwellings and landscape vegetation, and are somewhat protected by beach restoration and nourishment programs. Approximately 13 miles of the coastline in the study area is considered to be non-contributing. Continued sea-level rise, local tectonism, and reduction or cessation of coastal protective measures might well bring present non-contributing cliffs into an active role.

5. CLIMATE AND WEATHER FLUCTUATIONS

Introduction

5.1 Man has experienced long-term, worldwide variations in climate; from wet to dry (Figure 6) cold to hot, and stormy to benign periods. In addition these variations affect the rates of erosion by both marine and subaerial processes. In making estimates of changes likely to occur in the coastal area of San Diego County, therefore, one must have information about the occurrence and types of climatic changes in the past. The most important is whether or not the changes occurred gradually or suddenly. If the latter is true, a recurrence of stormy, wet climatic conditions would certainly increase the rate of erosion compared with that of recent decades.

Summary of Historic Climate Fluctuations

5.2 Emery and Kuhn (1982) examined geologic records and sediment core records from offshore basins, and meteorological indicators (rainfall records, tree rings, and sea surface temperatures), to document the climatic fluctuations that have occurred in southern California during the past century (Figure 6). Rainfall records in southern California are complete back to 1850, and from them the clearest trend in recent decades (Figure 6A) is the marked decrease in precipitation from 1947 to 1977. This benign period also is recorded in the tree rings (Figure 6C), as closely spaced tree-ring widths reflect low rainfall amounts and cool air temperatures. Figure 6B showing varve sediment thickness indicates the rate of deposition of silt and clay into offshore basins during years of rainfall (Figure 6B). Douglas (1976) compared tree-ring data back to 1671 A. D. with measurements of average ocean temperatures to 5 meter depths of southern California and Baja, California between 1924 and 1940, and 1942 and 1972, obtaining transfer functions that allowed estimates for water temperatures (Figure 6D). Because warm water in the region is linked with increased rainfall, Figure 6D corresponds reasonably well with Figures 6A and 6C.

5.3 The abundance of pelagic fish and atmospheric dust from large volcanic eruptions are not as closely linked with local rainfall. Past abundances of pelagic fish were obtained by Soutar and Issacs (1974) from counts of fish scales in the same Santa Barbara Basin cores from which varve thicknesses were measured. Their plots exhibit a general correlation of fish and rainfall abundance. Another indicator of climatic variations comes from the dust veil in the atmosphere produced by large volcanic explosions. Such data may be obtained from both historical records; and similar information that pre-date man and may be recorded in sedimentary strata. Dense veils reflect sunlight, usually reducing the temperature at the Earth's surface (Lamb, 1970; Bray, 1974; 1978; Ninkovich and Donn, 1976; Stommel and Stommel, 1979), and possibly increasing general storminess. Taking qualitative data into consideration (Figure 6), one can detect some general parallelism of indicators of past rainfall for southern California. The periods 1883-1892, 1934-1945, and 1978-present had unusually high rainfall and runoff. Large waves at sea during these periods were accompanied by substantial retreat of sea cliffs that destroyed railroad tracks and coastal roads in the 1880's; oceanfront lots, houses, and trains were destroyed in the 1930's and 1940's; and railroad trestles, piers, and houses were lost in the late 1970's (Kuhn and Shepard, 1979, 1980). The intervening periods 1842-1883 (except for 1851, 1862, 1867, and 1873), 1892-1934, and 1947-1977 generally had lower rainfall, less runoff, lower ground-water tables, and probably smaller surf. At least, the latter dry periods were times of sea cliff stability, except where construction by man was especially active. As a result, the sea cliffs generally displayed freshly exposed rock and strata during wet periods, then became covered with talus during the dry periods.

Regional Weather Patterns

5.4 The seasonal changes in rainfall are usually synchronous with large annual changes in the location of the source area of open-ocean storms (Appendix D, pl. 12, in Beach Erosion Control Report, March 1, 1960), which sometimes affect the study area's coastline. During the summer (Figure 7), waves from tropical storms and the southern hemisphere approach the San Diego region coastline from the southwest to west-southwest. During the winter, storms that originate south of the Aleutian Islands which generate relatively heavy surf and winter rainfall approach the study area's coastline from the west-northwest.

Catastrophic Storms and Floods of the 19th Century

5.5 To properly evaluate the dangers of erosion of coastal homes and of buildings on coastal lowlands along southern California, it is vitally important to know not only what type of storms are currently hitting the area, but also what has been the nature of storms that have occurred without warning during historical times. A careful search of historical documents now allows us to analyze a vast amount of information concerning the changing weather patterns during the past two centuries (Kuhn and Shepard 1983B, 1984). Their findings clearly indicate that the weather of the 30 years preceding the somewhat stormy year of 1978 was extremely free of conditions that would produce either extensive coastal erosion or flooding of coastal lowlands, but that during various periods extending back to the early portion of the 19th century, southern California was subject to severe storms quite unknown to us in recent years. Up to about 1856, shipping along the California coast was subject to occasional blows of an intensity described as a worse menace than those encountered in rounding Cape Horn, and accompanied by waves which may have been 50 to 60 feet high. These occurred during periods of warm water such as the type we seem to be having at the present time. Floods were of greatest importance in 1862 and again in 1884 intermittently to 1891. In addition to forming huge lakes in the interior of California, these storms flooded virtually all of the lowlands, destroying every house or other structure built there and ruining the newly developed railroads. Enormous quantities of sediment were washed to the sea along with logs and other vegetation, all of which was left on newly formed beaches. The rainfall was spotty, but included rates that have never since been equalled. These floods occurred largely without warning, although those of 1884 did occur shortly after the great eruption of Krakatoa Volcano. Just how this may be related is unknown.

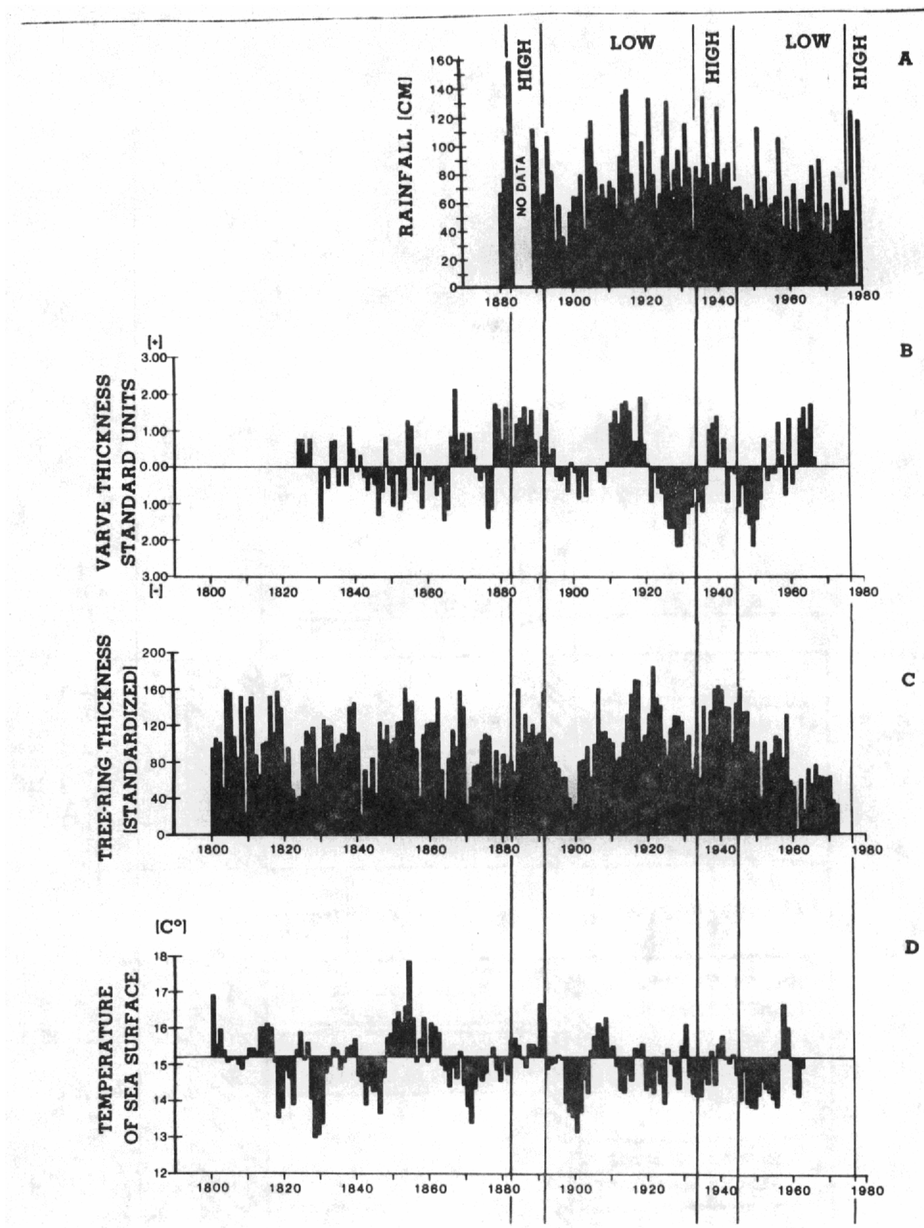


Figure 6. Rainfall measurements and other climatic indicators for southern California (from Emery and Kuhn, 1982).

A. Rainfall at Julian, 1880-1980.

B. Combined-core varve thickness index for Santa Barbara Basin expressed in standard unit form. Generally negative unit values from 1824 to 1859 reflect bioturbation (from Soutar and Crill, 1977, Fig. 7, p. 1166).

C. Standardized tree-ring indices for Pseudotsuga macrocarpa big cone spruce trees along steep slopes of Santa Ana Mountains (elevation 1,214 m.) (from Douglas, 1973; 1976, p. 188).

D. Winter sea "surface temperature 5 m below the surface at La Jolla (reconstructed from tree-ring data) (from Douglas, 1976, p. 188).

Note: The downward trend in rainfall is clearly seen in the rainfall (Figure A) and tree-rings (Figure C) complete figure from (Emergy and Kuhn, 1982).

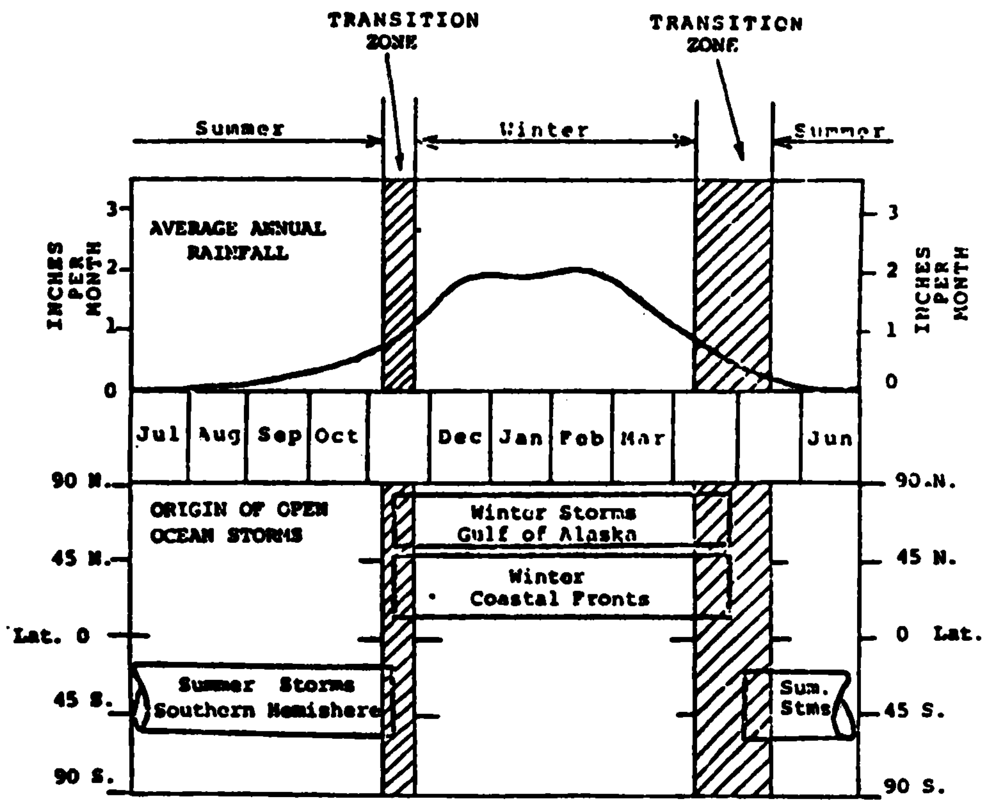


Figure 7. Wave sources, San Diego region (from Army Corps of Engineers Report #CCSTWS 84-4).

Note: 1. Rainfall data adapted from Pyke (1972) and
2. The latitude versus season plot of the source area for open ocean storms that affect the San Diego region was adapted from Munk and Traylor (1947): entire figure from Army Corps of Engineers Report #CCSTWS 84-4.

The Southerly Storms of The Early 1800's

5.6 Perhaps the most alarming thing we have learned from our historical research is about the violent storms of the early part of the 19th century, reported by ships' officers and by the famous Richard Henry Dana in his book "Two Years Before the Mast" (Kuhn and Shepard 1981, 1984). The book describes conditions along the California coast from San Diego north to Monterey during the 1830's.

5.7 Dana (1969), in his book "Two Years Before the Mast," recounted and described the "great winds" of the period which approached the coast from the southeast.

> "This wind (the south-easter) is the bane of the coast of California. Between the months of November and April, (including a part of each), which is the rainy season in this latitude, you are never safe from it, and accordingly, in the ports which are open to it, vessels are obliged, during these months, to lie at anchor at a distance of three miles from the shore, with slip-ropes on their cables, ready to slip and go to sea at a moment's warning. The only ports which are safe from this wind are San Francisco and Monterey in the north, and San Diego in the south."

These storms were described by Dana, as well as various ship captains as worse than the weather sometimes reported near Cape Horn.

5.8 They describe 50 and even 60 foot waves such as we have not encountered in recent years. These winter storms were said to have southeast winds, and it seems possible that they were of the same type as still hit Baja California today, called "Chubascos." There is considerable evidence that these storms occurred during a period when the water along the California coast was unusually warm. Between 1853 and 1857 the 'Blake' Railroad Survey identified and catalogued sub-tropical species of fish off San Diego. Hubbs (1948, 1960) found that numerous tropical species of fish fauna were recorded off of San Diego during the period of 1850 and 1870 and states:

> "In agreement with other lines of evidence, data on changes in the distribution of fishes along the Pacific Coast suggest that climatic oscillations have persisted into historic time. There are strong indications that the ocean temperatures from 1850 (or earlier) to about 1870 were definitely warmer in the southern half of California than during subsequent decades, and there are weaker suggestions of a reverse change in temperature and fauna during the past two or three decades [wet period of 1930 and 1940's]."

5.9 These severe storms ceased to be a regular occurrence around 1856 and apparently the last one to occur was during February 1891.

5.10 There is no doubt that floods of the past century were caused by rainfall much greater than any experienced more recently (Kuhn and Shepard, 1984). A remarkable flood occurred in San Diego during September and October, 1821, causing extensive damage (J.C. Hayes 1874). The water rose in a single night, filling the San Diego River in Mission Valley from bank to bank, washing away most of the ranches, and changing the course of the river. Amazingly, no rain fell along the coast at the time of the flood, so its source had to be in the mountains to the east.

1862 Flood Period. "The Noachian Deluge"

5.11 During the early years of the Civil War, in the winter of 1861-62, southern California, and the entire west coast of the United States, appears to have had a rainy season completely out of line with anything experienced since the white man came into the area (Kuhn and Shepard, 1981, 1984). The state was sufficiently populated at the time so that there is no doubt of the accuracy of the reports.

5.12 In the middle of a drought period [1842-1883] (Lynch, 1931) there occurred the greatest flood since the coming of the missionary fathers. The flood of 1861-62 was appropriately termed the "Noachian Deluge, and the winter was remarkable for extraordinary floods throughout the state. The rain commenced in November of 1861 and continued for more than half the time until February of the following year. One-hundred-two inches (eight and a half feet) of rain fell at Toulomne, near Sonora, between November 6, 1861 and January 31, 1862 (Farquhar, 1966). These rains resulted in devastating floods along the west coast of the United States from Vancouver, British Columbia southward through Baja California. Professor William Brewer stated at the time that, as of the end of January 1862:

> "It is supposed that over one-fourth of all taxable property of the state has been destroyed." (Farquhar, 1966)

5.13 Because of the bankrupt condition of the State of California as the result of the flooding that occurred during this single winter, the governor, state legislature and the state employees were unpaid for a period of a year and a half. The following is a documented account of the devastation caused by these floods throughout the State of California.

McGlashan (1921) stated:

> "In the winter of 1861-62 the entire West was visited by very heavy rains, which resulted in immense floods over all of the area. It is probable that the western rivers carried more water that year than in any other year since the coming of the white man. The Sacramento and San Joaquin rivers carried excessively large floods. Owens River raised its lake 12 feet. The Los Angeles River was heavily

flooded, but the data seem to indicate that the flood was less severe in Southern California than in the north."

Northern California

5.14 During the early months of 1862 Professor William Brewer stated that as of January 19, 1862 (Farquhar, 1966):

> "The great central valley of the state is under water -- the Sacramento and San Joaquin Valleys - a region 250 to 300 miles long and an average of at least 20 miles wide, a district of five thousand or six thousand square miles, or probably three to three and a half million acres! Although much of it is not cultivated, yet a part of it is the garden of the state. Thousands of farms are entirely under water - cattle starving and drowning."

5.15 The majority of the population of this area was forced to temporarily move to the coast around San Francisco due to the flooding. Hittel (1861) states that:

> "This result was the flooding of the greater portions of the Sacramento and San Joaquin Valleys and the driving of most of the country population to San Francisco. Within a week after the legislature convened, the city of Sacramento was almost completely submerged and communication with the capitol and from street to street and from house to house could only be maintained with boats. Nearly the entire country as far as the eye could reach north and south and all the way to the Coast Range of mountains on the west was a sea of water."

Southern California

Santa Barbara County

5.16 In Santa Barbara County the floods were also severe (Figure 8). The following is from the "Los Angeles Star," February 1, 1862:

> "Santa Barbara. The effects of the flood have been disastrous in this locality, to an extent unknown to the oldest inhabitant, a veritable and well known individual in these parts. At San Buenaventura the torrent rushed through the town with such force as to wash away the street to a depth of fifteen feet, carrying several houses with it. The town was abandoned, the people taking refuge in the church and elevated places. In the valley, the grass, timber and lands have been destroyed, and eight or ten houses knocked to smash. The gardens which were so famous in this locality were washed away, not a vestige being left. One man ran the risk of his life, having to wade waist deep carrying his wife and family to a place of safety. . . .The roads from here to Santa Barbara, as on

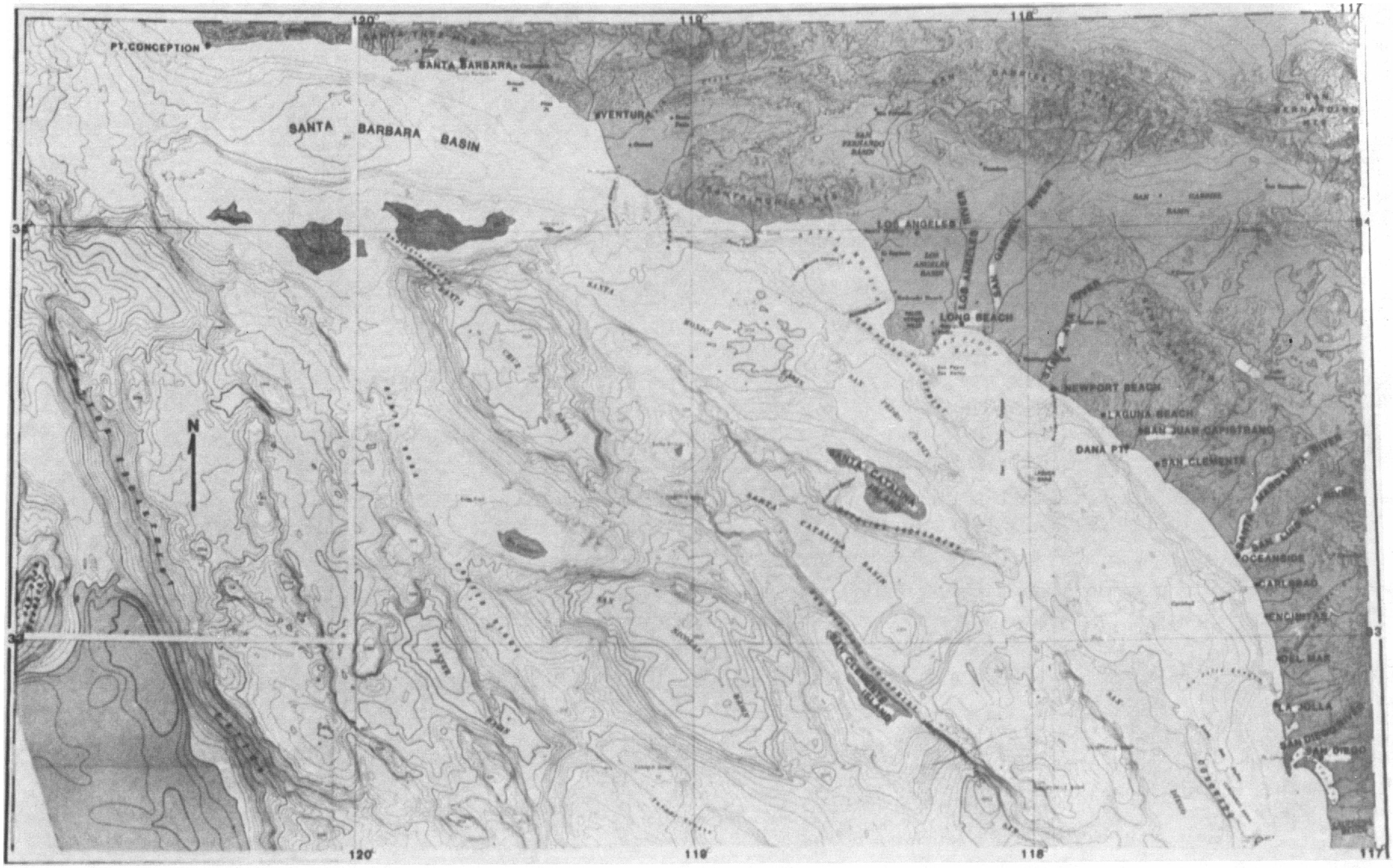


Figure 8. Location map showing areas affected by floods and storms between 1862 and 1947 (from Kuhn and Shepard, 1981).

all the other lines of travel, have been so cut up and washed away, that one can pass only on the hillsides, and that with great difficulty. It will be a long time, and cost a great deal of labor, to make the roads fit for travel."

Los Angeles County

5.17 Los Angeles County also reported severe flooding. Troxell and others (1942) give the following description:

> "During the flood period in 1862 the entire valley area from Los Angeles to the ocean, both toward San Pedro and toward Ballona, was a great lake. The Los Angeles River in the city of Los Angeles extended from Alameda Street to the bluff on the Pico Heights side.
>
> A little below Vernon, about where Vernon Avenue now is, the water split, and part of it went through Los [sic] Cienagas grant into Ballona Creek.
>
> During the same flood the San Gabriel River overflowed its banks, broke from its course east of El Monte, and started a new channel to the west of El Monte, taking about the same course as later taken in 1867 to form what was then known as New River".

5.18 In describing this flood, Guinn [1915] states:

> "The great flood of 1861-62 was the Noachian deluge of California floods. The season's rainfall footed [totaled] up to nearly 50 inches. The valley of the Sacramento was a vast inland sea. In our country, on account of the smaller area of the valleys, there was but little loss of property. The rivers spread over the low lands, but stock found safety from the flood on the hills. The Santa Ana for a time rivaled the "Father of Waters" in magnitude. In the town of Anaheim, 4 miles from the river, the water ran 4 feet deep and spread in an unbroken sheet to the Coyote Hills, 3 miles beyond. The Arroyo Seco, swollen to a mighty river, brought down from the mountains and canyons great rafts of driftwood which were scattered over the plains below the city and furnished fuel for the poor people of the city for several years. It began raining on December 24, 1861, and continued for thirty days."

Lake Elsinore

5.19 "The single wet season of 1861-62 filled the lake from almost complete dryness to a heavy overflow." (Lynch (1931).

San Diego County

5.20 Very few white American settlers lived along the coast to the north of San Diego during this early period. Small populations existed primarily near or on the Spanish Ranchos. Historical records occur in diaries, logs of vessels and surveys. A recent flood control publication (San Diego County 1976) compared all major floods of years past and noted:

> "Of all recorded floods, the flood of 1862 is considered by most to have been the largest. Rain began to fall on Christmas Day and and continued for about six weeks with intensity increasing on the last few days of the sixth week, when the worst flooding occurred. In San Diego's Mission Valley, the flow covered the entire valley floor. A dike was built to protect Old Town, but before the flood reached its peak, the dike was overtopped and portions of Old Town had to be evacuated. This storm held its peak for some 24 hours, which is considered a very long duration for a storm in southern California."

5.21 In Researching and writing the voluminous work entitled "The History of San Diego", Pourade (1966) reported that the flooding occurred with a violent sea storm from the south:

> "It was not only a flood of waters falling from the Heavens, but such a South-Easter I have never known, the tide backing up the waters of the bay which was running in from the river to a hight (sic) never before witnessed by Americans . . . all the old walls around town, which were not well protected, have gone down to rise no more. All the rivers of the county ran full, from hill to hill, and Hayes said that a George P. Abbotts thought a good-sized vessel might have gone a mile or more up the San Luis Rey River. . . .Roads were washed out over all Southern California, and there are reports that perhaps several hundred persons were drowned and that at least 200,000 head of cattle were lost either by drowning or starvation.

5.22 Apparently, not only was there great change in many river bottoms but also along coastals hilltops and in the back country as noted by McGlashan and Ebert (1918) when interviewing a Mrs. Swycaffer who lived above Mission Valley at that time:

> "Previous to 1862 the present site of San Diego (New Town) was on rounded hills; the draws and gullies now existing were begun in 1862. When Mrs. Swycaffer first visited the Warner Hot Springs, the springs broke out on a gradually sloping plain; the flood of 1862 made the topography as it is to-day."

Northern San Diego County

5.23 On February 1, 1862 the Los Angeles Star published a note from San Diego that stated:

> "The flood has been equally destructive here as in the other portions of the Southern Counties. The San Diego River spread over the [crease in microfilm] At San Dieguito lands and timber were washed away. At San Margarita, grass land, vineyards, fences, cattle. At San Luis Rey the flood cut an arroya [sic] fifty feet deep, carrying off a house, fences, lands, etc."

San Diego County Earthquake - 27 May 1862

5.24 Following close on the heels of the great flood there occurred on the 27th of May, 1862 what appears to be the largest earthquake since the coming of the white man. Legg, (1977) documented the earthquake and noted:

> "Judge Benjamin Hayes, after discussions with many residents following the May 27, 1862 earthquake in San Diego concluded that it was the severest felt in San Diego since the 1812 earthquake at San Juan Capistrano. [His account of this earthquake, upon which our description is mostly based, is in the Hayes "Emigrant Notes" in the Bancroft Library at Berkeley, Catalog No. CE62(Phot), pp. 690-691, 695, 697, 709-711.]"

5.25 This earthquake was evidently large enough to initiate landslides and bluff failures along the coast as noted by Hayes, (1862):

> "At La Playa, near Point Loma, water was thrown up out of the flat, sandy beach, cracks were formed, and the water of the Bay ran up on the beach more than three feet. There were many earthslides along the steep bluffs from La Playa to Point Loma, which may, in fact, have generated the surge in the Bay. The upper part of the brick tower of the Lighthouse on Point Loma, was severely cracked, but no windows were broken, nor was the light mechanism damaged."

Storms across the Continental United States: Winter 1861-1862

5.26 Evidently the unusual storminess and flooding that had been reported along the western United States during the winter of 1861-1862 was also occurring in many states East of the Rocky Mountains.

5.27 The "Daily Alta California" newspaper of 17 February, 1862 wrote of the:

> "Unusual Extent of the Flood -- The area of country over which the recent rain storm extended appears to have been commensurate with its duration and violence. How far south it reached is yet to be known, as well as, whether the storm which swept over the valley of the Ohio, raising that river to unusual height, was a part of the same storm or not. Its great extent north and south along the coast [Pacific], and the fact that eastern limits were not restricted to the line which usually bounds the winter storms of California in this latitude, for they rarely pass to the east of the main range of mountains, would indicate that this visitation had crossed the continent. It is seldom they are experienced on the Colorado district, and yet more rarely that they reach the river. But this storm raged with great fury far east of the Colorado."

5.28 General Ulysses S. Grant (Long, 1972) reported that prior to January 1862 the Mississippi River was very low so "that the banks were higher than the heads of the men standing on the upper docks of the steamer, but by the 8th of February, 1862 the river and tributaries became raging torrents and he noted:

> "the rain continued to fall so heavily that the roads became impossible for artillery and wagon trains".

5.29 Weather patterns similar to those being experienced in California were apparently the norm as General Grant stated that:

> "they had rain and snow, thawing and freezing alternatively."

5.30 Apparently land battles were suspended during this winter as a result of the intense rainfall.

5.31 One feature of the 1861-62 flood that should be borne in mind is that there seemed to be nothing which might have warned the residents that a flood was imminent. We seem unable to predict the occurrence of a similar event. Dry periods are irregular; some are very long, as the one preceding this flood of 1862, and others are quite short. Their termination is likely to be abrupt (Kuhn and Shepard, 1981).

Meteorological Synopsis - The Catastrophic Winter of 1861-1862

5.32 Because of the great damage which ravaged California and much of the eastern United States, it is extremely important to determine how such storms develop.

5.33 Much of the following information is drawn from the extensive historical research by Dr. Charles Pyke (1975). His work indicates that the ultimate potential for flooding during winter-type storms probably occurs when a series of cold, intense storms, caused by a high-amplitude blocking high offshore with a deep cold low pressure system, near the California Coast, are followed by a series of intense warm and very heavy storms which breaks under the blocking high pressure system.

5.34 Pyke (1975) wrote:

> "It appears that this could very likely have occurred in the fall and winter 1861-1862, when, according to historical accounts and a few early meteorological records, a prolonged siege of precipitation, alternating between cold storms with heavy snowfall and very warm and very heavy rains, pelted the far southwestern United States almost continuously for three months or more, and reaching a climax in middle and late January of 1862--the result of which was the most extensive flooding ever known (before or since) throughout much of California and parts of other States....Because of the severity of

these events, a number of historical accounts have been written and hydrometeorological studies conducted of the events of that winter.

5.35 According to the U.S. Weather Bureau (1943) precipitation in the area of the Sacramento River basin of California began as early as 9 November 1861 and persisted intermittently with only occasional significant letups through at least late January of 1862. Most precipitation amounts during November 1861 averaged about normal to somewhat above normal. This was followed about two to three times the normal precipitation in December and up to five times the normal amounts in January 1862. Above normal precipitation also fell during February of that season. The totals for the two calendar months December 1861 - January 1862 (U.S. Weather Bureau, 1931ff) include 23.68 inches (128% of long-term mean annual precipitation) at Sacramento, 33.90 inches (153% of mean annual) at San Francisco, and 45.35 inches (129% of mean annual at Shingle Springs (elevation 1415 feet) in the Sierra Nevada foothills near Placerville. About two-thirds of these December-January totals generaly fell within an 18-day period during mid-January. Considerably greater amounts than those listed here are likely to have fallen in the higher Sierras northeast of Sacramento, where mean annual precipitation in some places exceeds twice that of Shingle Springs.

5.36 At times during this extremely stormy period heavy snow fell over all of northern California and down to low elevations in central and southern California, while an exceptionally cold arctic air mass, with record-breaking low temperatures, prevailed over the Pacific Northwest United States. On several occasions during December 1861 and January 1862 these conditions rapidly gave way to very warm and very heavy general rains, as the cold air was replaced by the influx of unusually warm, moist air from out of the southwest. These heavy rains combined with the rapid melting of large quantities of snow to produce generally the worst flooding on record throughout most of California (U.S. Weather Bureau, 1943; McGlashan and Briggs, 1937; Hoyt and Langbein, 1955; Roden, 1966; Sidler, 1968; LaFuze, 1971; Lynch, 1931; and others).

5.37 The first of these major episodes of warm, heavy rain occurred over the northern portions of California on 7 December 1861. In Sacramento, the weather observer described the rain as "almost tropical," according to the U.S. Weather Bureau (1943). Another heavy rainfall period occurred in this region beginning on 22 December and culminated in severe flooding on 28 December. In southern California, meanwhile, a "a gentle rain," or "a nice, pleasant rain" began on Christmas Eve and continued through the Holidays (LaFuze, 1971; Sidler, 1968).

5.38 After the first of January the rains became generally harder and colder throughout the State, and heavy snows began piling up in all mountain area. On 5 and 6 January "severe snow showers" occurred in the foothills of the Sacramento Valley, and snow depths ranged from 6 to 12 inches over the valley floor only 12 to 30 miles northwest of Sacramento, according to the U.S. Weather Bureau (1943). From 8 to 11 January warm, heavy rains hit all of California melting much of the snow and producing disastrous flooding, particularly in the State's Central Valley, where the Sacramento Delta region is described as having become one vast lake, 20 miles wide and 250 miles long (U.S. Weather Bureau, 1943; Roden, 1966; and others).

5.39 During the ensuing days colder air once again settled into the far western United States, and between 15 and 18 January a severe arctic outbreak spread over the region, causing extremely low temperatures over the Pacific Northwest--with 16°F (-9°C) recorded even as far south and west as Fort Umpqua, near the coast of south central Oregon (Roden, 1966). In the intensifying baroclinic zone south of this extremely cold air, rainfall over southern California and snowfall over northern California increased. Then, beginning on 18 January another invasion of very warm and very moist air from the southwest spread over the entire Far West, with temperatures up to 59°F (15°C) recorded along the Oregon coast. Very heavy downpours resulted throughout California, again melting great quantities of snow, and resulting in unparalleled flooding throughout large portions of the State. In the Sacramento Valley the severe flooding of 9-11 January was repeated, and this time conditions extended over the northern portions of the basin as well. In southern California extremely heavy flooding was reported on a number of streams, including the greatest flood of record--by approximately a factor of three--on the Santa Ana River near San Bernardino on 22 January 1862 (Sidler, 1968), plus severe flooding downstream on this river in the Anaheim area (Hoyt and Langbein, 1955).

5.40 Toward the end of the month another extreme cold wave spread over the far western States, and more heavy snow was reported. In Sacramento three inches of snow was recorded in 18 hours on 29 January (U.S. Weather Bureau, 1943), and accounts of snow 16 feet deep in the San Bernardino Mountains of southern California on 6 February 1862 are cited by LaFuze (1971).

5.41 In Arizona a similar, but perhaps slightly less severe, precipitation and flood pattern is believed to have prevailed. Portions of the Gila River system are reported to have experienced flood crests second only to those of early 1891, and the peak 1862 flow at one location on the lower Colorado River is estimated to have perhaps exceeded all others, including that of 1891 and possibly that of 1884 (Smith and Heckler, 1955).

5.42 Although no weather maps or other meteorological analyses are directly available or this region during this period of time, some verbal sketches of the conditions across the far western United States have been put together by the U.S. Weather Bureau (1943) and by Roden (1966). These indicate for the heavier storm the likelihood of a strong frontal zone initially stretched across central or southern California and out into the Pacific to the southwest, with extremely cold air over the Pacific Northwest and with cold, northerly winds blowing down the Sacramento Valley. As each major cyclonic disturbance developed along this front and approached northern California and Oregon from the southwest, an overrunning and a great northeastward displacement of the cold air resulted in very heavy precipitation and rapid snow melt, according to the U.S. Weather Bureau (1943).

5.43 The sequence of meteorological conditions listed here, along with the precipitation events, suggest the greatest likelihood of a very high-amplitude, split atmospheric flow pattern--one in which the cold air from the north and the very warm, very moist air from the southwest were colliding almost directly over California. The extremely low temperatures in the Pacific Northwest and the occurrence of heavy snow over the low foothills and at times over the Sacramento Valley flood indicates the necessity of a high-amplitude configuration, with a very deep upper level trough or low over northern and central California. The sudden transition to very warm and very heavy rainfall over the entire region likely precludes a simple retrogression of this trough to an offshore position and the rather gradual infiltration of warm, moist air that would take place. More than likely a break-under type of storm from the subtropics was involved during each sudden warming and onset of heavy rain.

5.44 Further evidence of this type of synoptic pattern can be gathered from an examination of some of the rather few available mean temperature and precipitation records for December 1861 and January 1862 over other parts of the country (U.S. Weather Bureau, 1931 ff; Ludlum, 1968a). These sources tend to indicate for those two months significantly higher than normal temperatures over Tennessee and adjacent States, considerably lower than normal temperatures in Minnesota, around double the normal precipitation for those months across the central Great Plains and Mississippi River Valley, and near normal conditions along the central and north central Atlantic coast. This would tend to imply a broad low-latitude mean ridge over the south central United States, a cold upper trough and surface high over the northern Great Plains, a fast west-southwesterly jet stream and frontal zone across the central Great Plains, and a generally west-northwesterly flow over the middle Eastern Seaboard.

5.44 These downstream patterns would fit in well with a high-amplitude blocking high in the extreme eastern Pacific with a split flow: one branch of the jet stream shooting southward down the west coast of Canada and the United States, perhaps cutting back somewhat around a deep trough over northern and central California, and the other branch cutting under the blocking high and approaching central and southern California from tropical latitudes to the southwest, with the zone of convergence of these two branches of the jet stream likely shifting around by several degrees of latitude and longitude in conjunction with individual synoptic-scale disturbances--thus producing the alternating conditions between heavy snow and very heavy, warm rain in California.

5.45 As for the equatorial ocean temperatures during this period, one should expect from the relationships discussed in Pyke (1975) that the eastern equatorial Pacific Ocean in 1861-1862 would have been significantly cooler than normal or at least cooling down quite rapidly following a significant warm anomaly. The Southern Oscillation indices of Berlage were negative from 1859 to 1864--thus implying a fairly prolonged period of below normal eastern Pacific equatorial temperatures during these years.

5.48 It is also extremely interesting to note that the summer of 1861 was a season of an exceptionally heavy Southwest Monsoon in India. During this particular year all of the world's record rainfall amounts for every duration from one month (366.14 inches) to one year (1041.78 inches) and two years (1605.05 inches) were set at the highly orographically favored station of Cherrapunji, India (U.S. Western Bureau, 1960; and others)--the latter values covering a period which had begun in 1860. This would also tend to indicate a great likelihood of significantly below normal temperatures in the eastern equatorial Pacific Ocean, as can be seen from the following relationships.

5.49 It has been shown by Bjerknes, Walker and others that during periods in which the eastern equatorial Pacific Ocean is relatively cool, and the sea level pressure over the Indonesian region is generally low, the Walker Circulation will generally be quite strong--not only the branch of the circulation from the South American west coast to Indonesia, but also a branch of this tropical zonal circulation feeding into the Indonesian maritime continent from the west. During the Northern Hemisphere summer, this westerly branch over the Indian Ocean migrates and expands somewhat northward, and thus reinforces the Southwest Asian Monsoon.

5.50 Summer rainfall in India has been strongly correlated by Walker to the magnitude of the Southern Oscillation, and in fact this element is used by Dr. Walker as one of his components in the computational formula for the June-August Southern Oscillation Index. (A correlation coefficient of +0.76 has been computed by Walker and Bliss, 1932, between the component India rainfall and the complete June-August Southern Oscillation Index over the period 1875-1929.) Thus a year having a strong Southwest Monsoon over India is likely to be one of a positive Southern Oscillation Index (as computed by Walker) and a cooler than normal eastern equatorial Pacific Ocean (such as the year 1917), while a weaker Indian Monsoon in summer would likely be associated with a negative (Walker) Southern Oscillation Index and an eastern equatorial Pacific warm anomaly (such as in 1877).

5.51 Therefore, from the above discussions, one can be virtually certain that the unusual flood-producing conditions in California and other southwest States during the winter of 1861-62 were associated with a very high-amplitude, blocking high type of atmospheric circulation pattern in the northeastern Pacific Ocean, and that this pattern was most likely one having a split flow, with the two branches converging over or very near central California. One can also be quite certain that this extreme pattern occurred during, and was very possibly generated and maintained in part by, a considerably cooler than normal eastern equatorial Pacific Ocean and the various meteorological features resulting from this oceanic anomaly: a weakening and northward displacement of the intertropical convergence zone in the eastern Pacific, an intensification of convective activity over the maritime continent, an intensification of both the subtropical jet stream and the Hadley Anticyclone above the western Pacific, and the probable development of an intense Kona low or trough not far from Hawaii--a trough which served to maintain the northeastern Pacific blocking high, and a trough which on occasion opened up to the northeast and pumped extreme quantities of tropical moisture into California. Anomalous sea surface temperature patterns in the north Pacific Ocean also, of course, likely played a major role in the development and sustentation of the highly unusual atmospheric features which lead to these unprecedented California rains and floods."

Volcanic Eruptions and Their Impact on Climate

5.51 In 1815 the great volcanic eruption of Tambora occurred. This eruption was the largest in a series that occurred from 1811 through 1817. During this 6-year period Western Europe experienced cold spring and summer months, food shortages and late wine harvests (Bray, 1974). The period also encompassed a "year without a summer," 1816, as reported on the east coast of the United States and in western Europe (Stommel and Stommel, 1979).

5.52 Southern California, however, enjoyed good weather and larger crop yields were recorded following the eruption. It is estimated that more than 20 cubic miles of ash were ejected by the volcano (MacDonald, 1972) and the eruption was one of the largest during the past few thousand years (Rampino and others, 1979). The decade between 1810 and 1820 coincided with the most pronounced low in the mean sunspot record during the past 250 years, indicating a low solar ultraviolet output. This period was also a time of low magnetic intensity.

5.53 In August 1883 a major eruption of the Indonesian volcanic complex, Krakatoa, ejected nearly 4 cubic miles of ash (MacDonald, 1972). Seismic sea waves were generated which inundated and destroyed 300 towns and villages, 6000 ships at anchor and killed 36,380 people (Truby, 1971). The volçanic explosion sent miles of ash directly into the upper atmosphere.
G.A. MacDonald (1972) reported that:

> "Ash from the 1883 eruption of Krakatoa Volcano in the strait between Java and Sumatra is commonly believed to have drifted around the earth three times, refraction of the sunlight by the very fine dust in the upper atmosphere producing brilliantly colored sunsets as far away as England."

MacDonald (1972) also noted:

> "The famous American meterologist (sic), W.J. Humphreys, was convinced that a lowering of the amount of solar heat reaching the earth's surface, and consequently of average surface temperatures, during the years 1884-1886 was brought about by the eruption of Krakatoa in 1883; that a similar decrease during the years 1888-1892 was caused by the eruptions of Bandai in 1888. Bogoslof in 1890, and Awoe in the Gangile Archipelago in 1892."

5.54 Weather patterns throughout the United States and Europe changed abruptly following the Krakatoa eruption. It appears that the southern California climate changed from semi-arid to subtropical, with unusually heavy rainfall through June 1884. These subtropical storms came from the west southwest and not from the Aleutians (U.S. Signal Service, 1884). Killing frosts were reported in the Midwest and Northeastern states during June (U.S. Signal Service, 1884).

5.55 To make it more complicated, the heavy rains of 1884-1891 seem to have lasted longer than the volcanic effects and warm seas that marked this entire period (Kuhn and Shepard, 1984).

5.56 It may very well be that a long-term cooling trend on the earth triggers the volcanic activity which assists in cooling, producing a change in the cyclonic storm pattern that could also produce warming trends in other areas. Fairbridge (1980) states:

> "The largest eruptions of the last 100,000 years have all occurred well after the initiation of a cool cycle."

This includes both the Tambora eruptions in 1815 and Krakatoa in 1883. It therefore seems likely that volcanic activity is not the primary cause of rapid climate fluctuations, but may be the triggering mechanism that initiates certain wet periods.

Previous Studies: 1880's & 1890's

5.57 Baker (1948) and Ganus (1976) studied tree-ring data and determined that the period 1883-84 through 1893 was a wet one. The U.S. Geological Survey (Troxell and others, 1942, McGlashan, 1921) studied the hydrological implications of this period and documented the damage as a result of flooding. Pyke (1975) investigated this period and described the meteorological conditions of the period, with emphasis on 1884, 1889 and 1891.

5.58 This wet period is also documented in Scientific publications i.e. (Nature and Science, The Monthly Weather Review of the U.S. Army Signal Service, U.S. Coast and Geodetic Survey notes, and reports to the Superintendant of the U.S.C.G.S.).

End of a Drought Period: 1880-1883

San Diego County

5.59 Between January 1880 and January 1883 the California Southern Railroad surveyed the land and subsequently filed and registered maps with the Federal and State governments showing railroad roadbed right-of-way, (Figures 9, 10) depot and water tower locations (Figure 11) between San Bernardino and San Diego in southern California.

5.60 The railroads of this period are extremely valuable as a lesson in land-use planning. The California Southern Railroad, which was completed in

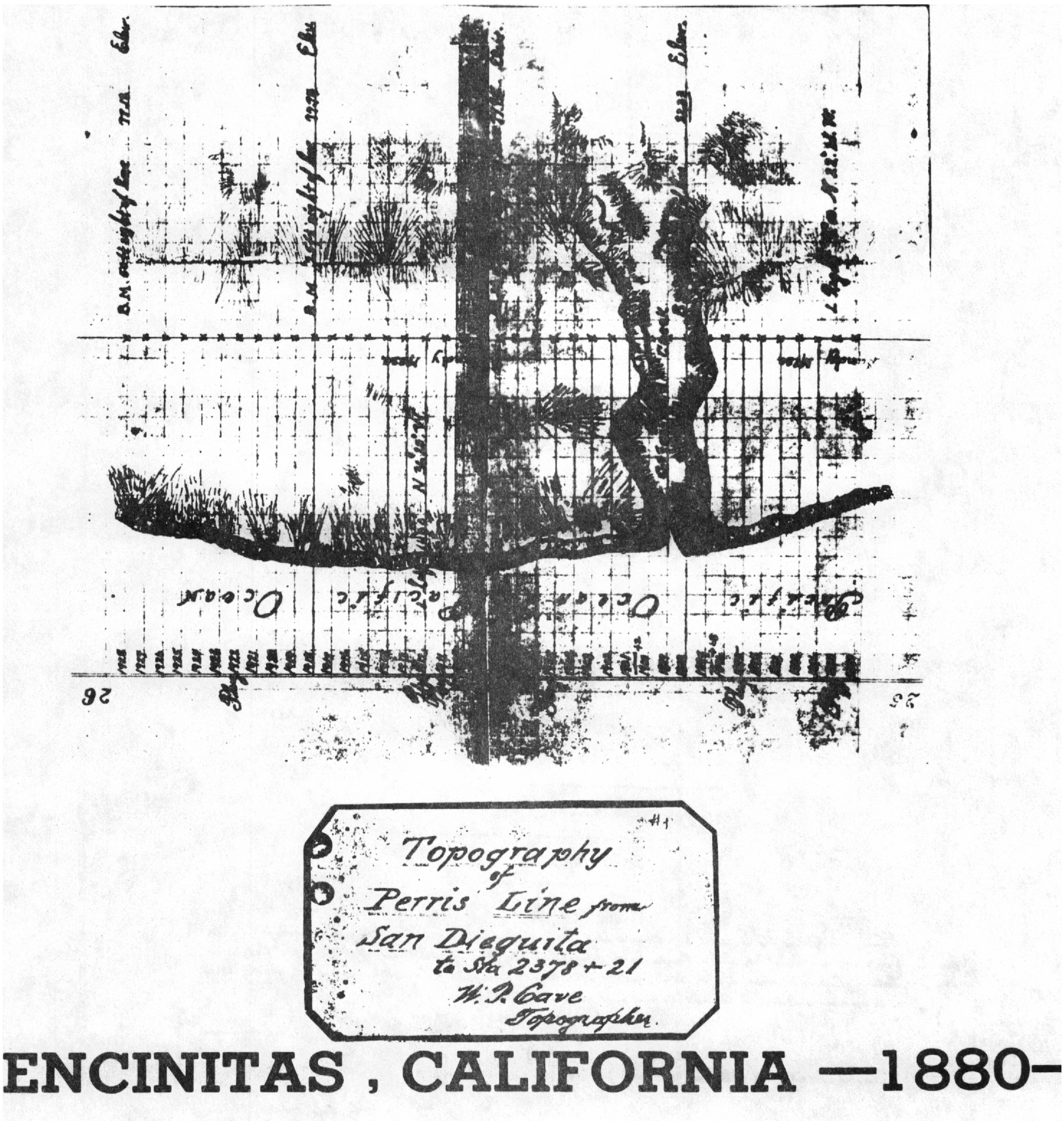


Figure 9. 1880 survey map for proposed location of California Southern Railroad at Encinitas (from California State Archives, Sacramento).

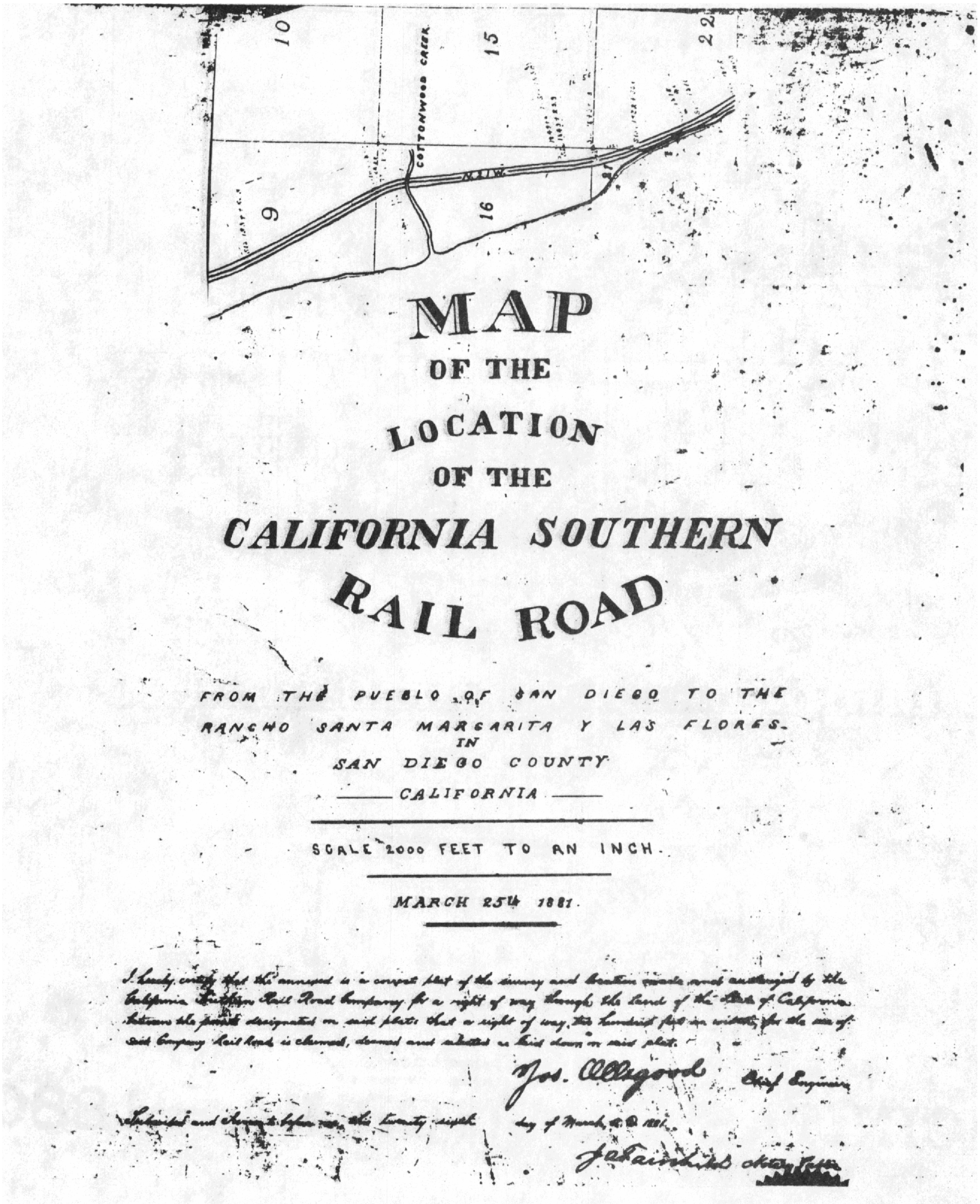


Figure 10. 1881 map of the location of the California Southern Railroad (right of way map) (from California State Archives, Sacramento).

Figure 11. 1883 map of the location of the California Southern Railroad through San Diego County (from California State Archives, Sacramento).

1883, was bankrupt in 1884. The railroad had located most of its railroad trestles across the then dry, river gorges, barrier sand bars, and floodplains, only to be destroyed by massive floods between February and March of 1884.

5.61 Prior to March of 1883, no surveyed, platted town existed between the City of San Diego in the south and San Juan Capistrano in the north, a distance of 60 miles. The majority of the existing residents lived on the California Ranchos.

5.62 Between 1870 and 1890, the U.S. Government and California Township Plat Surveys were completed in southern California and filed with the U.S. Surveyors General's Office at San Francisco, California.

5.63 In March of 1883, the County Surveyor, L.L. Lockling surveyed and staked out a section of Federal land in northern San Diego County, later to be called Encinitas (Little Green Oaks) (Figure 12). This was the first platted coastal town north of the City of San Diego (San Diego County Subdivision Map #148).

The Great Intermittent Floods of 1884 to 1891

5.64 An abrupt climatic change along southern California began during the wet-stormy winter of 1883-1884 and continued through 1891 (Kuhn and Shepard, 1981, 1884) (Figure 13). The weather was characterized by tremendous downpours; the highest daily, monthly and annual rainfall levels on record in San Diego County were during this period. The winters of 1884, 1886, 1889, 1890 and 1891 brought unusually severe cyclonic sea storms to southern California. The intense rainfall caused sediment saturation of the bluffs, and large storm swell coupled with high tides coincided with river basin flooding. There were also severe storms during the summer and fall months of 1889 and 1891, (U.S. Army Signal Service, 1889, 1891).

Storm Year of Record: 1883-1884

San Diego County

5.65 The winter of 1883-1884 was the wettest on record in San Diego County (Figure 14). The following rainfall was recorded throughout San Diego County in a 3 month period, with the largest amount following in February and March 1884 (Figure 15) (data from County of San Diego, Sanitation and Flood Control records).

Location	Elevation in feet	Rainfall in inches
San Diego	20'	25.97"
Camp Pendleton area	250'	30.83"

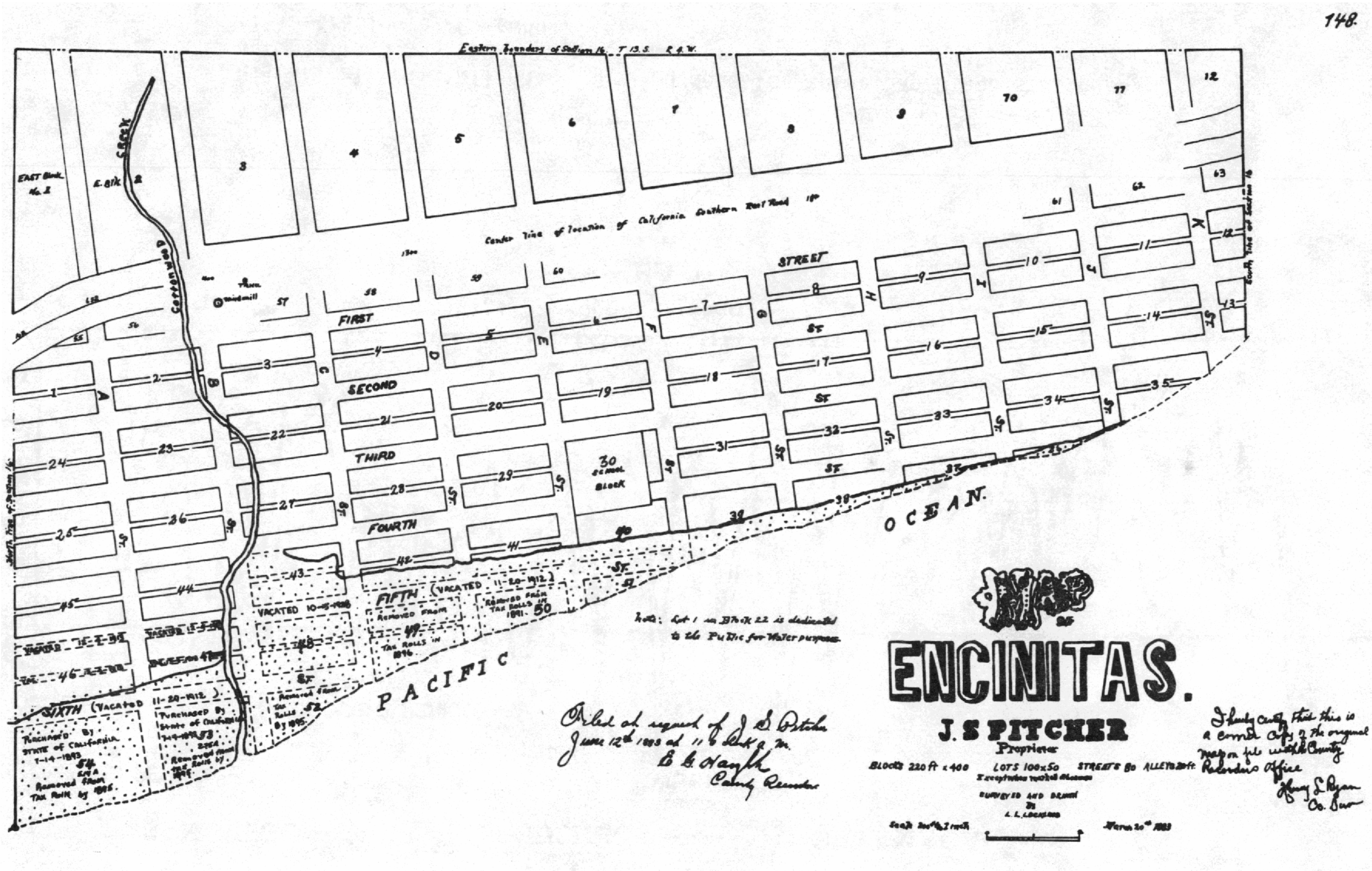


Figure 12. 1883 Town Plat Survey of Encinitas, Califonria. (Dotted area indicates blocks and streets removed by County assessors from tax rolls) (Map #148 from County of San Diego Surveyor Office).

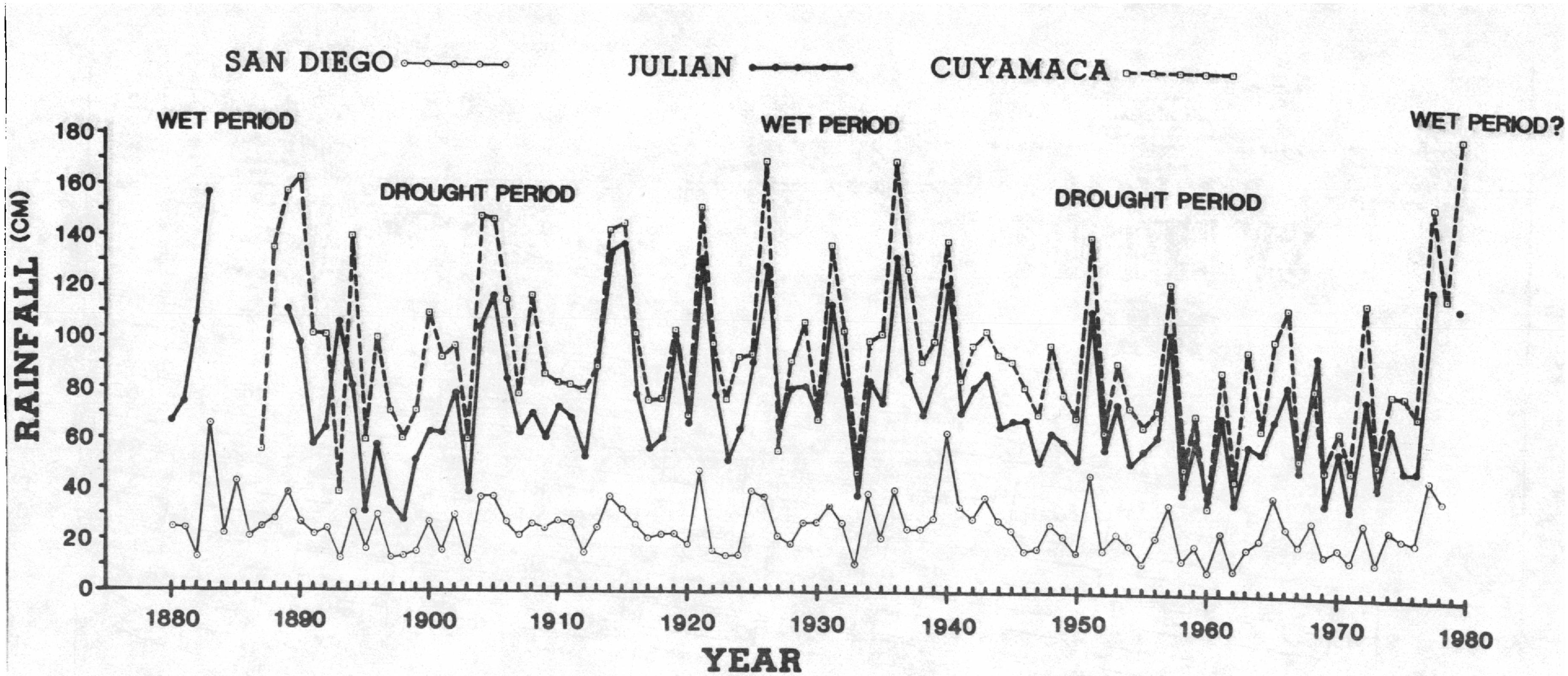


Figure 13. Historical rainfall chart showing data for three San Diego stations between 1880 and 1980. Data from Hydrology Section, County of San Diego (illustration by G. Kuhn).

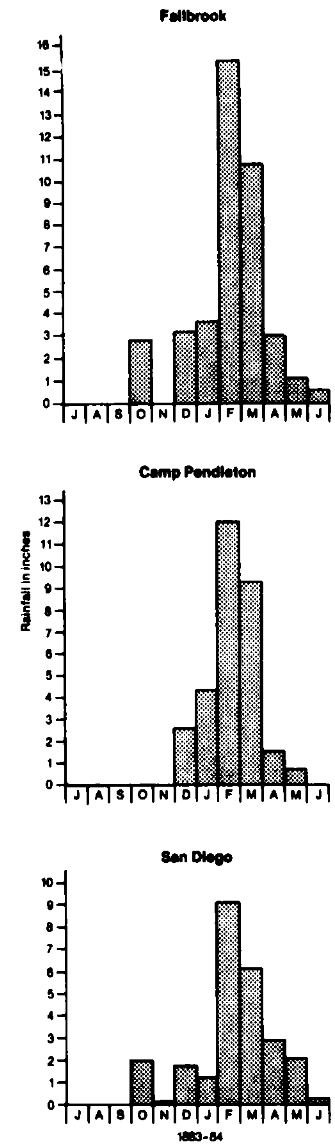
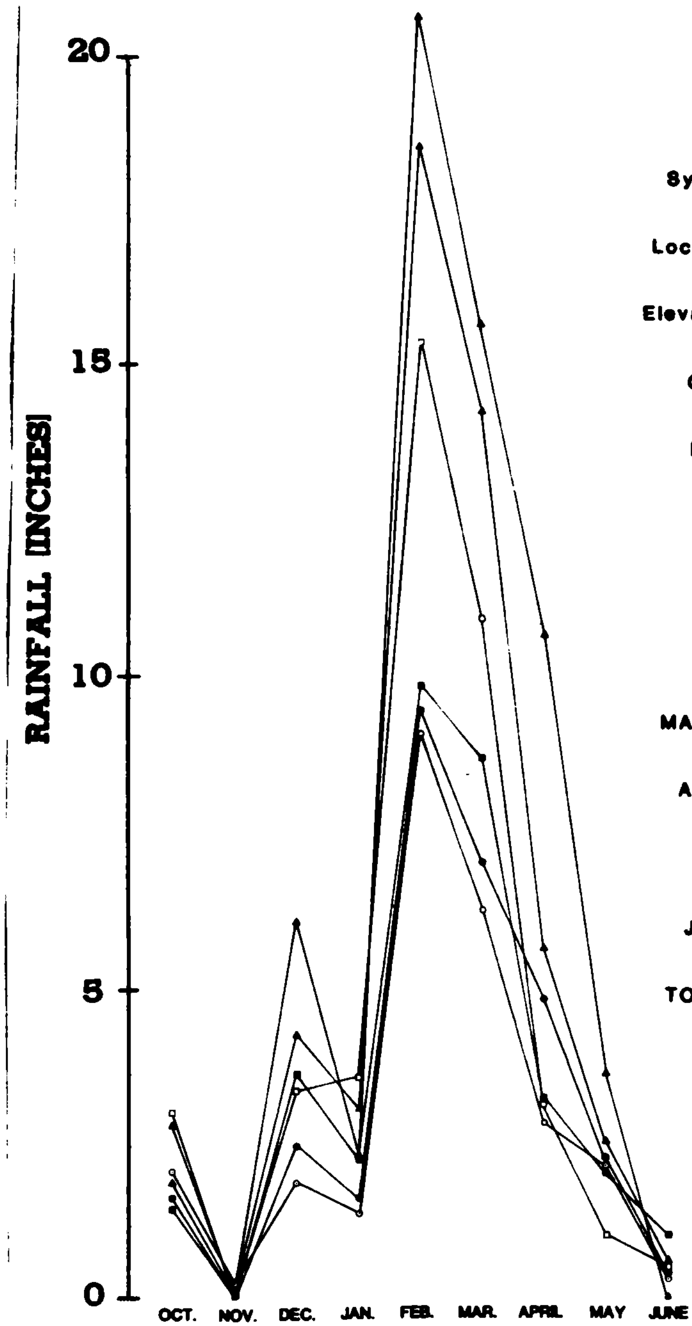


Figure 14. Rainfall at San Diego, Camp Pendleton and Fallbrook for the water year 1883-1884. (Note: Rainfall was heaviest on record at San Diego, 25.97"; Camp Pendleton, 30.83"; and Fallbrook, 40.77". Fallbrook was destroyed by flood (data from Hydrology Section, County of San Diego).



Symbol	○—○	●—●	□—□	■—■	△—△	▲—▲
Location	San Diego	Poway	Fall Brook	Escondido	Valley Center	Julian
Elevation	98'	460'	700'	1020'	1400'	4200'
OCT.	2.01	1.59	2.96	1.46	1.85	2.75
NOV.	.20	--	--	--	--	--
DEC.	1.82	2.40	3.32	3.58	4.22	6.00
JAN.	1.34	1.59	3.56	2.22	3.00	2.25
FEB.	9.05	9.40	15.36	9.83	18.50	20.63
MARCH	6.23	6.96	10.90	8.66	14.20	15.63
APRIL	2.84	4.81	3.13	3.26	5.61	10.63
MAY	2.17	2.26	1.02	2.00	2.52	3.63
JUNE	.31	.44	.52	1.05	.61	--
TOTAL	25.97	29.45	40.77	32.07	50.51	61.52

RAINFALL 1883-1884

Figure 15. Graph of rainfall recorded in San Diego County during the great wet year of 1883-1884. Note: the large rainfall during February-March 1884 (graph by G. Kuhn).

Poway	460'	29.45"
Fallbrook	700'	40.77"
Valley Center	1360'	50.51"
Julian	4200'	61.52"
Cuyamaca	4270'	65.00"*

*estimated

5.66 In 1884 there were two separate floods. The first was in February, when the railroad line to San Bernardino was washed out, and for nine months San Diego was cut off from San Bernardino. Several miles of track and all but one bridge between Encinitas and San Diego were washed out, and it was nearly two months before the rail connection between Encinitas and San Diego was reestablished (Kuhn and Shepard, 1984).

5.67 Food supplies ran out in Encinitas so a ship was dispatched from San Diego with ten tons of provisions for the stranded settlers. But the heavy rain continued falling, and the waves were breaking far out in the kelp beds or even farther away, so the vessel stayed offshore for over a week, waiting for chance to unload its supplies. A great gale then approached from the southeast, and the ship ran for the lee of Santa Catalina Island. After remaining there for another week the vessel returned to San Diego, its cargo still undelivered (Kuhn and Shepard, 1984).

5.68 In early February, 1884, the San Diego Union reported the damage which occurred along the line of the California Southern Railroad south of the present town of Del Mar (Figure 1).

> "Construction trains were sent out with repair crews to shore up the weakening roadbed by "cribbing" it with extra ties and timber. At the Cordero station in Soledad Valley two huge landslides covered the tracks and they had to be dug out, but new slides occurred almost as fast as the others were cleared away."

5.69 The California Southern Railroad station, located directly to the north of Oceanside, near the Santa Margarita Ranch house, reported on 14 February 1884, that in fourteen days rainfall totaling thirteen inches had fallen. This was more rain than had fallen at the same location during the entire previous year. Severe storms were reported throughout San Diego County (Kuhn and Shepard, 1984). The mountainous region to the east was affected by the storms, as reported by the San Diego Union (26 February, 1884) following one cloudburst on the southwest slope of Palomar Mountain:

> "Cloud Burst on Smith's Mountain--A private letter from Agua tibia near Pala, dated on the 19th says: "We had the most awful storm Sunday and Sunday night, I ever saw or heard. None of us slept that night. It was frightful. About half past four on Sunday afternoon a terrifying crashing and roaring was heard, and standing in the door we saw a wall of water, seventy feet high, coming down the creek, tearing trees, huge boulders, etc. to pieces, roaring and

and boiling in its course. It was a frightful sight. Everything was swept before it. Enough wood was crushed up by this torrent to give us firewood for years. The once thickly wooded glen is swept bare as a sandy beach on the ocean shore. Every tree, shrub and branch is gone. It is absolutely desolate. Surely great destruction must have been wrought along all water courses in the county."

5.70 As of April 1, 1884 the California Southern Railroad, which had begun operations between San Bernardino and San Diego only a year earlier, announced to its stockholders that it was bankrupt and in debt $200,000-$250,000 [1884 Dollars] as a result of the storms and flooding. By the second week in June 50 to 80 inches of rain had fallen throughout the back country of San Diego County, and the rains began to lessen. By July 1 the rainy season was over (Kuhn and Shepard, 1984).

Los Angeles County

5.71 The year <u>1884</u> may have been the most severe with respect to the area of flooding and landslide activity. News articles and other references describe widespread flooding extending from southern California to central Arizona. Some references suggest that essentially all bridges were destroyed between Los Angeles and Tucson. Tentative age dating of some of the larger previous landslides of southern California indicates an approximate age of 100 years, which would be in agreement with the assumed damage attributed to the storms of 1884 (Slosson and Krohn, 1982).

5.72 Troxell and others (1942) noted in a U.S. Geological Survey Water Supply paper that in Los Angeles and surrounding areas, "The flood of 1884 ranks among the major floods--in fact, there were two floods in 1884. The first came the latter part of February; it did little damage, but a great quantity of water fell, apparently utilizing much of the absorptive capacity of the ground. A second flood came within 6 or 8 days after the first and did a great deal of damage. All the bridges across the Los Angeles River were washed out except one, the old Downey Avenue Bridge. Many houses were washed away, and several people drowned. The water broke out of the river banks and flowed toward Alameda Street, which was lower than the river bed; came up on First Street halfway between Los Angeles and Main Streets, and also flooded the lower part of the city. At Maple and Twenty-fourth Streets the water was between 3 and 4 feet deep. The flood waters flowed westward along the then Washington Road and Jefferson Street and thence southwest into Ballona Creek through which it reached Ballona Bay. All of the Cienega country became a great lake, and the country back of Venice a veritable sea".

5.73 "San Fernando Valley was flooded from Chatsworth to Glendale. The southern Pacific railroad was washed out in many places."

5.74 "The Santa Ana River cut a new channel to the sea. Beginning at a point below where Santiago Creek enters the Santa Ana, the river cut through the fertile lands east of the old channel and discharged into the ocean about 3 miles southeast of its former outlet."

5.75 "The year of 1884 proved to be the great flood year of later times, and 37.50 inches were reported during the season for San Bernardino, while over 40 inches were registered at Los Angeles and more at other points."

Ventura County

5.76 Troxell and others (1942), went on to state:

> "In Ventura County, 30 inches of rain fell in 27 days, of which 6 inches fell in 34 hours, causing the Ventura River to rise higher than it had been since the flood of 1867. It was estimated that 65 inches fell during February and March in the San Antonio Valley, whose drainage is tributary to the Ventura River, causing the worst flood known in the valley. Casitas Bridge, crossing Ventura river at Foster Park, was washed out."

5.77 The floods of 1884 brought huge quantities of sedimentary material to the sea as a result of great flooding in river basins and gullying of the bluff face along coastal terraces. This sediment helped to develop an extremely wide beach, created large deltas at river months. The beaches were covered with debris and driftwood that was later used for firewood for years (Kuhn and Shepard, 1984).

Storm Years of Record: 1886-1887

5.78 This year was particularly severe at Los Angeles (Figure 8). Heavy rainfall caused streams to reach a rapid flood stage. Troxell and others (1942) noted:

> "The great flood of 1886 reached its first serious state on January 19th. All of Los Angeles between Wilmington Street and the hills on the east side was inundated; levees were carried off as if they were so much loose sand and stubble, and for two or three weeks railway communication with the outside world was impossible".

Storm Years of Record: 1887-1947

5.79 For the purpose of this study only those storms which occurred between 1887 and 1947 are listed. A list of those storms that occurred between 1948 and 1986 may be found in U.S. Army Corps of Engineers Report CCSTWS 87-2, prepared by Kuhn and others (1987).

5.80 The U.S. Geological Survey (Troxell and others, 1942) documented a history of floods in southern California between 1770 and 1938, and a companion

U.S.G.S. water supply paper (McGlashan and Ebert, 1918) documented the 1916 storm-flood year.

<u>Major Flood year of Record</u>

December	1889
February	1891
December	1909
January	1910
March	1911
Jan.-Feb.	1914
January	1916

5.81 Troxell and others (1942) also noted that:

> "No major floods occurred in the Southern California region between 1916 and 1938", except a localized flood in January of 1934 in La Canada Valley. Minor floods caused damage in certain areas during 1918, 1921-22, 1926, 1927, 1931, 1932, 1934, 1936, 1937."

5.82 Marine Advisors (1960) made a study of wave conditions at Oceanside at the time additional harbor entrance structures were being designed to accommodate the Oceanside recreational harbor. They examined daily historical weather maps and newspapers for storm damage that had occurred between 1891 and 1958. The storm dates are listed below:

Feb. 23-34, 1891	April 6-8, 1926
Dec. 17-18, 1902	Mar. 14-15, 1930
Mar. 9-11, 1904	Feb. 3-5, 1931
Dec. 10, 1906	Dec. 10-17, 1932
Feb. 20-21, 1909	Dec. 7-12, 1934
Jan. 21, 1912	Feb. 2-4, 1935
Jan. 31, 1912	May 27-30, 1935
Mar. 8-10, 1912	Dec. 20-22, 1935
December, 1913	February 3, 1936
Jan. 25, 1914	Feb. 20, 1936
Dec. 16-17, 1914	Mar. 11-17, 1937
Jan. 28-30, 1915	Dec. 6-12, 1937
Feb. 1-3, 1915	January, 1938
Apr. 29-May 1, 1915	February, 1938
Jan. 26-28, 1916	March 2-3, 1938
Jan. 28-30, 1922	Sept. 15-25, 1939
December, 1924	Dec. 24, 1940
Feb. 1-2, 1926	Jan. 22-25, 1943
Feb. 13, 1926	Dec. 1-6, 1945

5.83 Marine Advisors (1960) state that the most severe waves occurred, in order of intensity, on:

1. September 24-25, 1939,
2. March 9-10, 1904, and
3. January 28-30, 1915.

5.84 The County of San Diego Department of Sanitation and Flood Control (1976) documented the most-significant storm-flood years since 1862, and concluded that no severe storms capable of producing floods had occurred since 1938.

Storm-Flood	Years
February	1891
March	1906
January	1916
December	1921
February	1927
Feb.-March	1938

Tropical Storm Years: 1889-1891

5.85 Between 1889 and 1891 the southern California area was once again battered by numerous record-breaking subtropical storms, accompanied by exceptionally heavy rainfall. During this period the U.S. Coast and Geodetic Survey was conducting topographic and bathymetric surveys along the coast of San Diego County. The USCGS (1889) topographic notes indicate the bluffs showed "...new erosion during each winter storm as the characteristic feature of this coast."

5.86 During the year between 1889 and 1891, southern California experienced violent subtropical storms and exceptional record heavy rainfall (Kuhn and Shepard, 1981, 1984) (Figures 16, 17).

Record Rainfall at Encinitas:

12 October 1889

5.87 One exceptional storm hit Encinitas in San Diego County on the evening of 12 October 1889 (U.S. Army Signal Service, 1889), and between 10 p.m. of the 12th and 6 a.m. on the 13th, 7.58 inches of rain fell during that 8 hour period (U.S. Army Corps of Engineers, 1977), (Figure 18). The rainfall and subsequent flooding was reported to have:

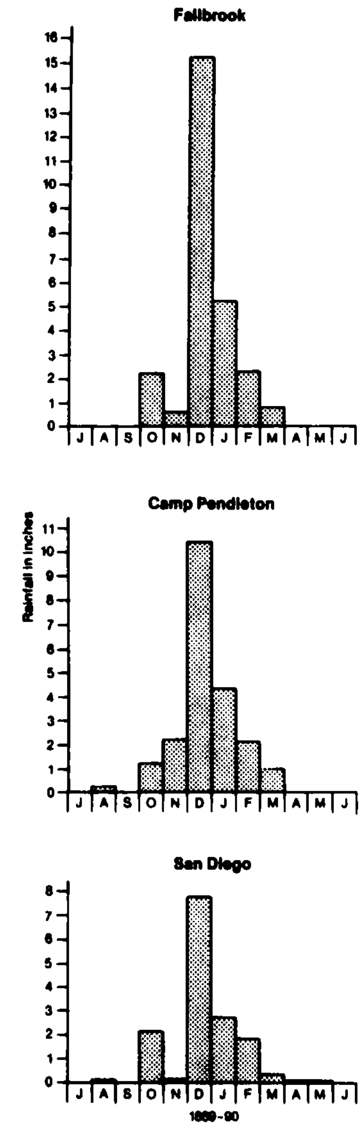


Figure 16. Rainfall at San Diego, Camp Pendleton, and Fallbrook for the water year 1889-1890. (Note: Rainfall amounts were: San Diego, 15.02"; Camp Pendleton, 21.97"; and 26.91" at Fallbrook. (Most of the rain fell in December 1889) (data from Hydrology Section, County of San Diego).

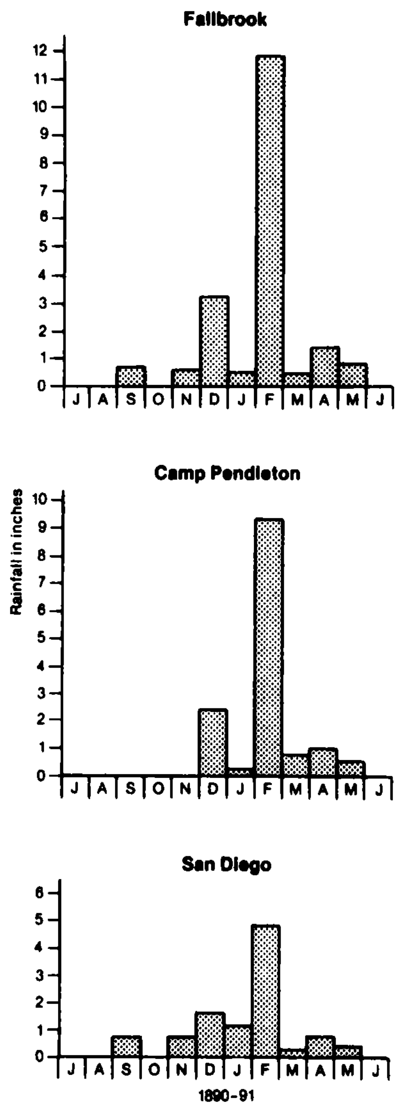


Figure 17. Rainfall at San Diego, Camp Pendleton and Fallbrook for the water year 1890-1891. (Note: Rainfall amounts were: San Diego, only 10.47"; Camp Pendleton, 14.22"; and 19.68" at Fallbrook. Most important is that much of the rain fell in a 10 day period in February 1891 (data from Hydrology Section, County of San Diego).

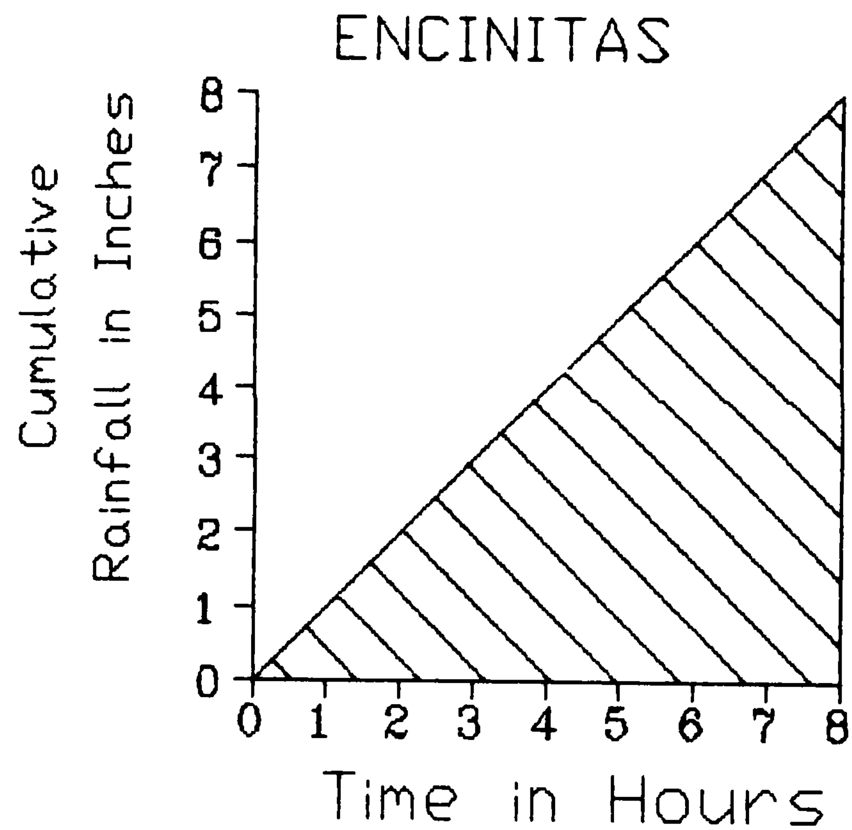


Figure 18. Rainfall recorded at Encinitas, California which occurred on the night of 12-13, October 1889. An amount of 7.58" of rain fell in an 8 hour period (from U.S. Army Signal Service Monthly Weather Review for October, 1889).

"Caused considerable damage; the storage reservoir at Cottonwood Canyon broke, and a large body of water rushed down the valley, washing away the railroad bridge and doing much injury to ranches" (U.S. Army Signal Service, 1889).

5.88 The San Diego Union (15 October 1889) also wrote that rain:

"Completely inundating [sic] all the low lands; reports of damage to the farmers are coming in from all sides, and the extensive damage to the county roads renders travel impossible."

5.89 There is little synoptic weather information for the storm of 12 October 1889, but the U.S. Army Signal Service Monthly Weather Review Summary for this date included a chart of tracks of areas for October 1889 (Figure 19).

5.90 The U.S. Army Corps of Engineers (1981) for N.O.A.A. and U.S. Dept. of Commerce examined this historical information and storm track data and reported:

"One track, labeled VI on this figure, is especially interesting, and we believe it may offer a clue on the nature of Encinitas storm. Track VI enters the coast near Monterey, Calif., near 1800 PST of the 12th (0200 GMT on the 13th). Although the track shown in Figure 19 represents an extratropical storm system, it is unusual in its southerly landfall and direction of movement. The direction of the track at its coastal encounter suggests it may have come from a more southerly position, and we speculate that this storm may, in fact, have been a tropical cyclone that traveled northwards along the California coast and regenerated in mid-latitudes as an extratropical system."

5.91 Examination of 1885-1891 San Diego County Tax Assessor records of land parcels located at and south of the mouth of Cottonwood Creek, Encinitas, indicate that the seaward property was devalued, and land parcels directly inland increased temporarily in value (Figure 20). (Kuhn and Shepard, 1981, 1984).

5.92 Severe storms were also reported at Los Angeles, according to the Monthly Weather Review (October 1889):

"The Signal Service observer at Los Angeles, Cal., reports that 3.16 inches of rain fell at that place from 8:15 a.m. to 4:45 p.m. on the 20th, flooding street and cellars; submerging the engine house of the cable road, and stopping the engines. He further reports that from this date showers occurred daily until the 23rd. On this latter date 1.87 inch fell and numerous washouts occurred on the railroads centering in that city; the Santa Monica Line of the Southern Pacific Railroad suffering the severest damage from a

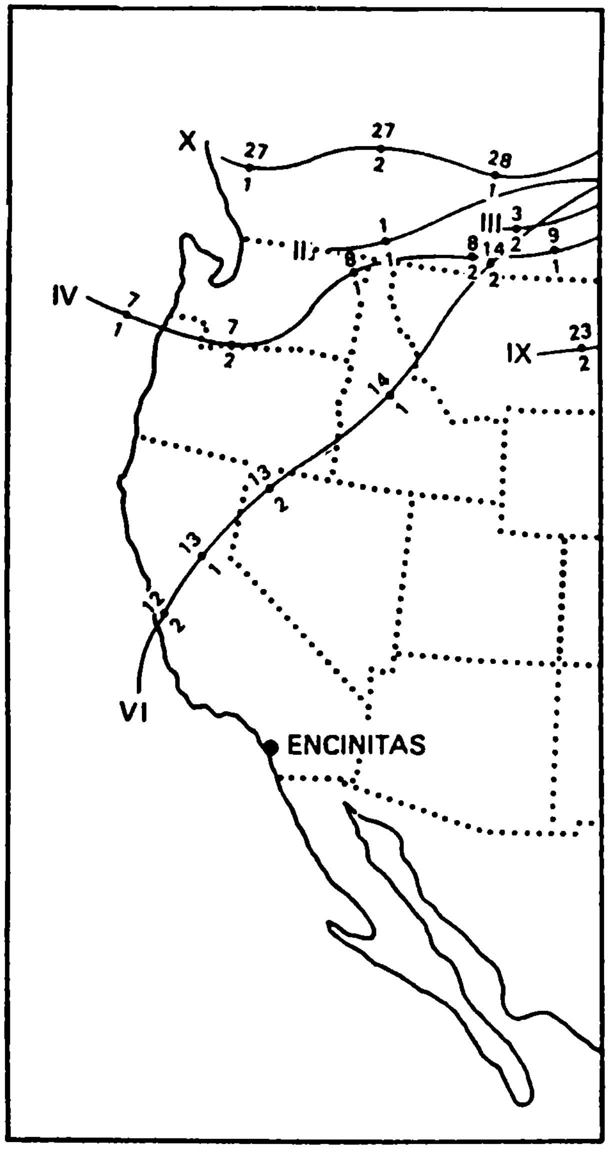


Figure 19. Storm tracks on the west coast of the United States for October 1889 (data from U.S. Army Signal Service Monthly Weather Review, 1889).

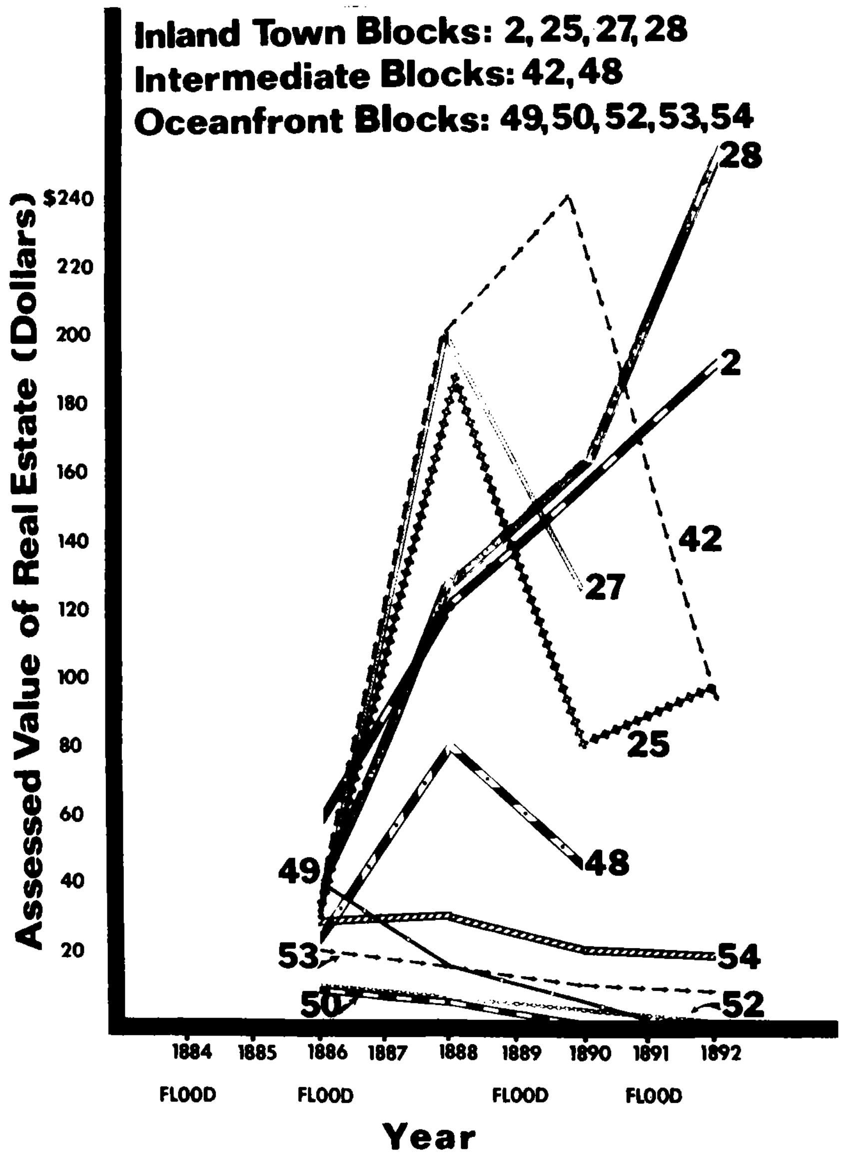


Figure 20. Assessed value of former oceanfront and inland subdivided blocks and lots in Encinitas in 1880's. As former seaward parcels of land were devalued, the block directly inland temporarily increased in value (data from San Diego County Tax Assessor Records, 1886-1892).

reported cloud-burst in the Santa Monica Mountains, which also destroyed a considerable portion of the Los Angeles and Pacific Railroad."

November 1889

5.93 In November 1889 northern California experienced very heavy rainfall, over 10 inches for the month, while southern California rainfall was less than one-half of an inch. (Accurate records of coastal changes, wave heights and damage were kept by California branches of the United States Coast and Geodetic Survey during this period.) The topographic branch of the Survey was in the process of mapping the coastline at the present Sites of San Onofre and Camp Pendleton north of San Diego in 1889, and stated:

> "During November [1889], although there had been a heavy rainfall, the precipitation had been generally at night, and field work was not seriously interfered with, but by the middle of December the rains had become almost continuous and the soil so saturated with water that the pack-animals would bog down on the grassy slopes of the mountain, and under such conditions progress was necessarily slow. Finally, however, the San Onofre sheet was completed, and on December 22, Mr. Rodgers began his arrangements for leaving the field. These were not carried out without many difficulties and annoying delays, owing to the swelling of the streams, wash-outs, and carrying away of bridges on the railroads, and other effect of heavy rainfall, resulting in a temporary suspension of freight and passenger transportation. From the 25th to the 31st of December the party was hopelessly weather-bound at Capistrano, and it was not till January 6 that passenger-train service was resumed to the northward from Los Angeles." (U.S. Coast and Geodetic Survey, Report to the Superintendent 1891).

5.94 The Coast and Geodetic Survey (1889) also stated in their field notes that during this wet winter the bluffs showed:

> "New erosion during each winter storm as the characteristic feature of the coast."

December 1889

5.95 The Monthly Weather Review of December 1889 reported:

> "On the Pacific coast the greatest excesses in precipitation were noted along the California coast from San Francisco to Los Angeles where the rainfall for the year was more than twelve inches greater than the average annual average amount and where at Los Angeles the excess for the year was nearly sixteen inches."

5.96 Precipitation to equal or exceed 2.50 inches in twenty-four hours was reported at thirteen stations in California on the 8th, 10th to 12th, 15th, 20th, 22nd, 24th and 25th. 4.30 inches fell at Los Angeles on the 11th-12th; 3.50" were recorded on the 8th at Los Gatos and 1.0 inch fell in less than two hours at Pasadena on December 24th (Monthly Weather Review, December 1889).

5.97 The U.S. Geological Survey (Troxell and others, 1942) investigated this flood year and noted:

> "The flood of 1889 was comparable in magnitude to that of 1884. It came on Christmas Day, and the greatest damage occurred on that day. The Evening Express, Los Angeles, in its issue of December 26, 1889 says:
>
> "The storm was general all over the southern section of the State. No trains on the Santa Fe or S. P. [Southern Pacific] have either arrived or departed except one to Santa Monica. Levees in numerous places have been washed away. Hon. H.T. Gage says that the new San Gabriel, the old San Gabriel, and the Los Angeles Rivers have formed one body near Downey and are sweeping toward the ocean, carrying everything with them. On the Laguna Ranch a lake 5 miles in width has formed, and the water is nearly to the top of the hay stacks. The Los Angeles River, 2 miles below the city, has swerved from its channel and is running down the Downey Road".

San Diego County

5.98 Flooding also was reported in San Diego County, as follows from the special anniversary edition of the San Dieguito Citizen (1953):

> "1889 was Year of Big Floods, Del Mar and District Inundated: The year 1889 is still remembered by some old timers in San Diego county as the 'year of the big rains.' The area from Del Mar to Encinitas and Oceanside was inundated. The San Elijo and San Dieguito, Los Penasquitos and Los Batisquitos lagoons were rush torrents of water. In these areas railroad lines, roads and other communication lines were washed out."
>
> "Disaster struck all of Southern California in December, 1889. That was the year of the great rains. They cut railway service, washed out roads and bridges, drowned livestock and washed away crops."

5.99 The weather varied greatly from month to month throughout the world during the winter of 1889-90. This stormy condition seems to have been general throughout much of the United States at that time. (Kuhn and Shepard, 1981). See Appendix I for the exceptional weather events recorded for the January to December, 1890 by the U.S. Army Signal Service in the monthly Weather Review (December 1890).

Record Storm Year: 1891

January 1891

5.100 While Californians experienced quite mild weather during January 1891, Western Europe was reeling from the effects of an extreme record cold wave. The Monthly Weather Review for January (1891) reported:

> "During the period of 41 days from December 13th to January 22nd the minimum temperature fell below the freezing point on 21 days at Vienna, Munich, and Stockholm; on 40 days at London and Brussels; on 39 days at Berlin; on 37 days at Paris; on 25 days at Leith; on 6 days at Rome; on 2 days at Algiers; and on one day at Lisbon. Over the south part of England, where the mean temperature for December was more than 10° below the normal, the cold spell was reported the most persistent since 1814, although the temperature was not exceptionally low nor the snowfall remarkably heavy. Over the north part of the British Isles the mean temperature was above the normal. Over the west part of the continent of Europe the winter will number among the most severe of the century. In Austria the cold was unprecedented in a quarter of a century."

February 1891

5.101 During February of 1891 there were destructive floods in California, Arizona and on all major rivers east of the Rocky Mountains (Kuhn and Shepard, 1981, 1984). Extremely large snowpacks existed in southern California prior to the warm rains that occurred from February 17 through the 27th, 1891.

5.102 In parts of California and Arizona the rainfall was remarkably heavy. In the extreme northwest part of California the precipitation total for February 1891 exceeded 20.00; at Boulder Creek, Santa Cruz Co., 34.03 was reported; and at Cuyamaca, San Diego Co., a depth of 32.20 was reported. The monthly precipitation also exceeded 10.00 in Yayapai Co., central Arizona. (Monthly Weather Review, February 1891).

Some of the heavier rainfall for this period which fell in an extremely short period of time are listed below: (Data from Monthly Weather Review, 1891).

Location	Rainfall	Time period
Cuyamaca, Ca.	22.40"	22-23 Feb.
Julian, Ca.	7.48"	23-24 Feb.
Oakland, Ca.	6.65"	15th Feb.
Campo, Ca.	6.40"	21-22 Feb.
Stonewall Mine, Ca.	23.90"	21-24 Feb.
Farleys Camp, AZ	6.45"	17-18 Feb.

San Diego County: 19 February, 1891

5.103 The rain began to fall on 19 February and the great flood soon followed. Pourade (1965) recorded:

> "The San Diego River quickly rose to flood level and hundreds of residents flocked to ride the cable cars to the pavilion park overlooking Mission Valley. A solid sheet of water spread across the valley floor and over the tide flat to False Bay. Every telephone and telegraph line was out, railroad connections were severed and a heavy storm at sea with gale winds interrupted shipping. Virtually everything that had been built in the riverbeds or on the alluvial plans between the great watersheds and the sea was gone or reduced to wreckage."

5.104 Pourade (1965) also noted that:

> "Bear Valley [located south of Escondido, near the present "Wild Animal Park"] reported thirty inches of rain in thirty-seven hours; Cuyamaca, eighteen inches in forty-eight hours. The city [San Diego], however, recorded only 2.56 inches for the storm and 4.77 inches for the month......"

> "In that day the town of Tijuana straddled the border and consisted of thirty or forty residences and business houses. The storm washed away perhaps twenty-five of them, as well as the trees which shaded the town. Those who rebuilt moved to higher ground, and laid the foundations for the present cities of Tijuana and San Ysidro. Elsewhere in the county, Campo suffered heavy damage and the little settlement of Foster, three miles north of Lakeside at the end of the San Diego & Cuyamaca Railroad track, disappeared. The Lakeside Hotel was nearly wrecked."

5.105 During the month of February 1891 the storms, heavy rainfall and flooding destroyed the railroad tracks in Temecula Gorge. Following this stormy year the section of railroad line between Fallbrook and Temecula was abandoned and a new "surf line" was routed along the coast from Los Angeles to San Diego. There was also major damage during the month in the state of Arizona, as recorded in the Monthly Weather Review for February, 1891.

Arizona: 23 February, 1891

5.106 "All streams in Arizona were extremely high. At Yuma the river was 29 feet 6 inches in the morning, but had been higher during the night. At 9 a.m the water on Main street had fallen about 3 feet below its highest point. All telegraph wires were down. In many parts of the territory the streams were higher than ever before known, and farms and irrigating ditches were badly washed."

Arizona: 24 February, 1891

5.107 On the 24th, the Colorado, Salt, and Gila Rivers were rising rapidly. At Holbrook and Fort Thomas the rivers were the highest ever known and great damage occurred while bottom lands along the Gila and San Francisco rivers were underwater.

Arizona: 25 February, 1891

5.108 On the 25th of February, 1891 Yuma reported the Colorado River was flowing 25 miles wide at the former crossing and the U.S. Army had evacuated the entire town. Pourade (1965) recorded that:

> "Two days later [February 27] a wall of water from the western slopes of the Rocky Mountains passed through Yuma, raising the river thirty-three feet above low water mark. The next day [February 28] nothing remained but a railroad bridge, the Southern Pacific Hotel and the Yuma prison. The town was gone and twenty miles of railroad were gone with it. Fourteen hundred people had been made homeless. Lakes formed in the Salton Sink, in the deepest depressions of the Imperial Valley."

5.109 Much of the most recent arroyo cutting and channeling of streams and rivers occurred in southern Arizona and coastal southern California during this wet year (Cooke and Reeves, 1976).

Los Angeles County

5.110 At Los Angeles, the barometer fell to 29.50, (corrected to sea level), the lowest reading recorded during a winter storm; the lowest barometer previously recorded being 29.52 during the great storm of February, 1884. An immense amount of damage was caused in that region by floods and freshets. (Monthly Weather Review, February, 1891).

5.111 Floods and freshets prevailed in southern California as the result of heavy rain. Railroad and telegraphic communication was generally cut off from Los Angeles, California washouts occurred and bridges were destroyed on the railroads. No material damage was done in the City of Los Angeles. The Los Angeles River washed away its banks in many places north of the city, destroying much valuable property. Considerable property was destroyed in the San Fernando Valley. South of the city, the Los Angeles River changed its course, taking the old channel toward Ballona from which it was diverted during the storm of December, 1889, flooding the country and destroying much valuable property. The San Gabriel River was diverted into a new channel some distance above Duarte, making a current about 1,000 feet wide, which, rushing along with irresistible force, flooded the country below lower Duarte, and three persons were drowned (Monthly Weather Review, February, 1891).

5.112 Mr. Finkle a resident who lived in Los Angeles during February 1891 noted (as reported by McGlashan, 1921):

> "There was an extremely violent flood on the San Gabriel River, but I have no data from which to compute its volume. I recall, however, the first trip I made to Los Angeles, after communication by rail was restored, that the debris cone of the San Gabriel was completely littered with drift of all kinds, and that a large black bear drowned and washed down in the flood, was lodged in a large amount of debris near the Santa Fe Railway crossing over the San Gabriel, and that the new channel of the river west of El Monte was cut to a width of a great many hundred feet in that storm, where it had only been about 75 feet before. At the Santa Fe and Southern Pacific crossings the San Gabriel had completely washed them out for a long distance across the country, requiring about two weeks to be replaced. The town of Azusa was entirely washed away and was reestablished in its present location after the flood."

5.113 The great flooding ended in March 1891.

5.114 August 1891 was the warmest August recorded until that time along the Pacific Coast (U.S. Signal Service, 1891). Paradoxically, although no rainfall was reported over the greater part of California or stations in the lateau region, a world record rainfall was verified at Campo (near the Mexican border) on August 12, 1891 when 11.5 inches fell in eighty minutes (Figure 21), (U.S. Weather Bureau, 1960, U.S. Army Corps of Engineers, 1981). The U.S. Weather Bureau (1960) noted:

> "Examination of a photocopy of the original observation form showed that the shower started at 11:40 a.m. and ended at 1:00 p.m. with the amount of precipitation recorded as 11.50 in.".
>
> "According to the observer's written notes the overflow cylinder of the gage overflowed twice, and an unknown portion of the precipitation was lost. In the observer's own words:
>
> On the 12th of August had a Cloud burst. One heavy thunder cloud came up and rained about 30 minutes verry [sic] hard raised the watters [sic] in the streams flood high by the gague. I could not tell it was running over. I emptied it and then another cloud came up and the one that had part pased [sic] over drew back and the two came together and it poured down whole watter [sic] nearly. I went to the gague [sic] again in 30 minutes and it was running over and the reservoir was nearly half full. I emptied it out of the gague [sic] and did not Stop measure the water to measure the reservoir and after the shower was over I went out to and the gague [sic] was gone

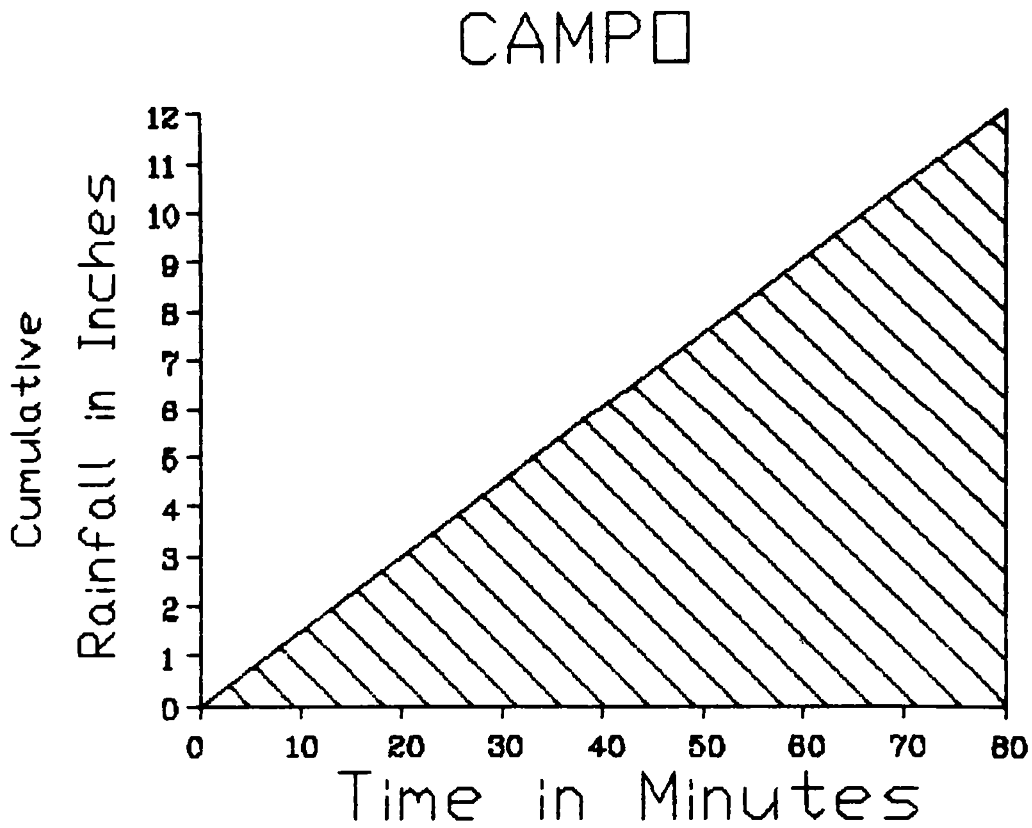


Figure 21. Record rainfall that fell at Campo, California on August 12, 1891: An amount of 11.5" fell in 80 minutes (data from area verified by U.S. Weather Bureau (1960), U.S. Army Corps of Engineers (1981).

carried off by the flood. It was exciting times with us about that time. A few days later, August 25, 1891, Mr. Gaskill wrote to Sacramento for a replacement rain gage. ...the 12th of August when we had a watter [sic] spout and rained in 60 minutes the gague [sic] twice full and and soon after I emptied the gague [sic] the second time the watter [sic] rose so rapidly that the gague [sic] was carried off in the great flood of waters we had all we could do to save our selves. I did not report to you before because I thought probably I might find the gague [sic] but I have made several diligent searches and cannot find it. After I emptied the gague [sic] the second time it rained about 30 minutes longer which I did not have any means of measuring as everything was afloat."

December 1891

5.115 During December 1891 numerous storms did considerable damage along the north Pacific coast. The Monthly Weather Review for December 1891 reported:

> "A remarkable succession of cyclonic areas from the north Pacific Ocean caused unusually stormy weather on the north Pacific coast and during the latter part of the month the storms which visited that region were notably persistent and severe."
>
> "A report from San Diego, Cal., dated the 11th [Dec. 1891] stated that rain was badly needed, and that the ground was too hard and dry to plow. The drought in that section was broken by rain the latter part of the month." (Monthly Weather Review, December 1891).

5.116 The significance of these exceptional floods from 1884-91, so far as coastal erosion is concerned, is perhaps greatest as the rains that produced them were very concentrated. Similar, but less intense rains in more recent times have caused heavy erosion of sea cliffs. One can well imagine how these much more concentrated downpours would have cut deeply into the cliffs and canyons and resulted in myriad landslides far greater in effect than anything observed in recent years.

Meteorological Synopsis of the Greatest Storm years between 1884-1891

5.117 Pyke (1975) researched the meteorological implications for the period between 1884 and 1891. He reported that among all the seasons of heavy southwest United States rainfall prior to 1900 that occurred around the times of major equatorial warm anomalies, three years were "historically quite outstanding". Those years were the season 1883-1884, 1889-1890, and 1890-1891.

5.118 See Appendix II for a description of the atmospheric and meteorological implications of ths period as written by Dr. Charles Pyke in 1975.

The Years 1892-1893

5.119 Above normal rainfall was recorded in San Diego County in that year. No severe floods were reported.

The Years 1893-1903

5.120 The period between 1893 and 1903-04 was one of extreme drought in southern California. Lynch (1931) reported:

> "In 1893 began a drought which still holds the record as the most acute since the advent of the Americans. It was not as severe as that between 1821 and 1832, but was of about the same length."

The wettest year during this period in San Diego County was 1902-1903 (Figure 22).

Infrequent Floods during the Early Half of the 20th Century

5.121 Above normal rainfall was reported for this period, though there were deficient years (Lynch, 1931). 1904-1905 was a wet year (Figure 23). Heavy floods occurred in 1911 at Ventura; in 1914 at Los Angeles; and in 1916 at San Diego.

Flood Year: 1911

Ventura

5.122 In March 1911 there was a serious flood on the Ventura River. January and February of that year were rainy months. Although no excessive downfall occurred, the soil was wet and conditions were ripe for a rapid runoff following the heavy rain of March 9. According to the Ventura Free Press for March 9, 1911, "The Ventura River perhaps was never higher. It is overflowing its banks for Casitas to the sea. The Casitas Bridge, 17 feet above the water at normal flow, is underwater; the Avenue is awash; the western part of Ventura is under water; at 3:15 the big steel bridge [Southern Pacific Railroad] broke and 50 feet of the structure went down and out into the ocean." (Troxell and others, 1942).

Flood Year: 1914

5.123 Floods in January and February 1914 were very destructive in southern California, especially the Los Angeles and Santa Barbara areas. U.S.G.S. Water Supply Reports No's #391 (1914) and #447 (1921) cover aspects of the flooding and contain estimates of peak discharges available for this period.

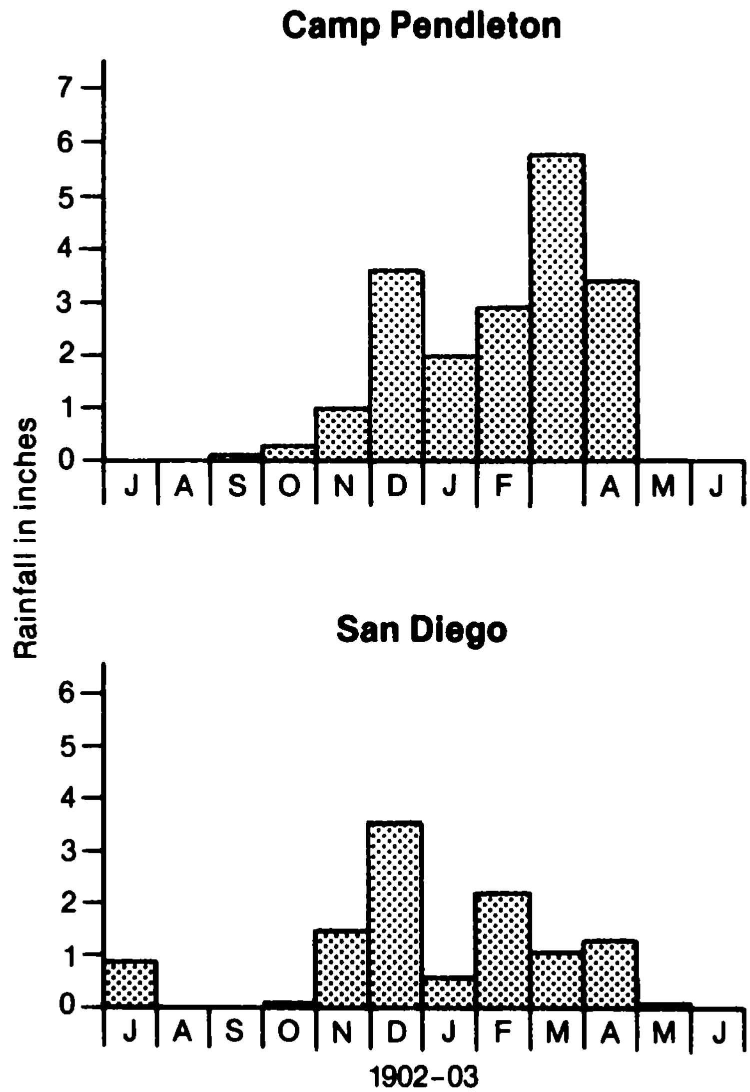


Figure 22. Rainfall at San Diego and Camp Pendleton for the water year 1902-1903. An amount of 11.76" fell at San Diego, while 19.57" fell in the Camp Pendleton area (data from Hydrology Section, County of San Diego.)

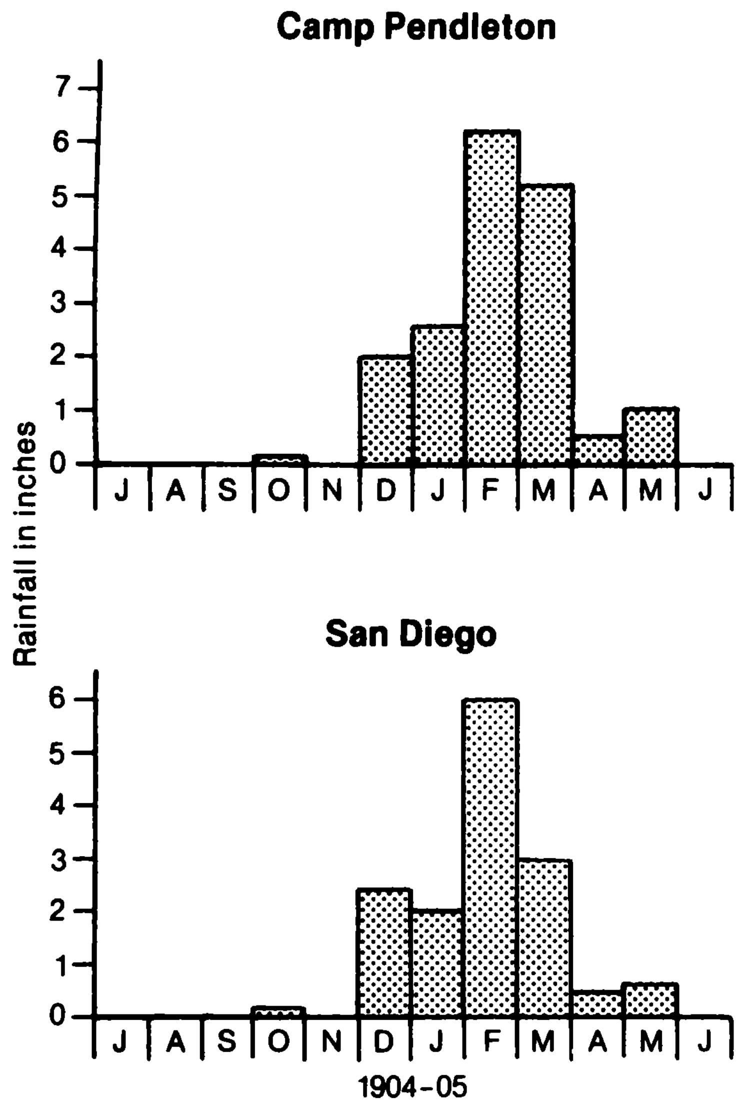


Figure 23. Rainfall at San Diego and Camp Pendleton for water year 1904-1905. An amount of 14.32" of rain fell at San Diego, while 20.20" fell in the Camp Pendleton area. At Pendleton the rainfall was very concentrated in February-March 1905 (data from Hydrology Section, County of San Diego).

Record Flood in San Diego County: 1916

5.124 The most significant flood of the present century in San Diego County was in 1916 (McGlashan and Ebert, 1918). San Diego County Dept. of Flood Control (1976) indicated:

> "In the early days, before 1916, homes and ranch buildings were built on high ground overlooking valley floors. But as population increased, land values also increased. The valley floors were then used for agricultural purposes and people settled close to their cultivated fields for convenience, thus encroaching on the flood plains. This was the situation in January 1916. There were actually two separate storms in the month of January 1916 causing two separate floods. The period of the first storm was from 14 January to 21 January".

5.125 The U.S. Geological Survey (McGlashan and Ebert, 1918) used U.S. Weather Bureau data from the Monthly Weather Review for 1916 and indicated tht the storm fronts came from the Hawaiian Islands and the heavy rains fell on the 17th and 18th of January - They noted:

> "The resulting floods were severe and much damage was done to railroads, bridges, highways, land under cultivation, and to the harbor of Los Angeles, by reason of the mass of silt deposited thereon."

5.126 The second storm locally hit San Diego County from 25 January to 30 January. The first storm had been preceeded by 3 to 4 days of light rain and the water-storage reservoirs were nearly full. The San Diego County Dept. of Flood control 1976 report indicated:

> "Both storms fell on a saturated watershed which rapidly carried the flow to the rivers. When the first storm hit, the streams were converted from normally dry creek beds to torrents that soon overran their banks, causing widespread damage from the Santa Clara River to the Mexican border and from the mountain divide to the Pacific Ocean."

5.127 The flood damage from the second storm was even greater than from the first. On 26 January and 27 January winds were reported at 30 to 54 miles per hour from a southerly direction. The San Luis Rey River valley was inundated from bank to bank for about 1.5 miles, covering an area of about 1,000 acres and destroying all the farms in the lower portion of the valley. After the waters subsided, three to six feet of sand and silt covered the area and heavy debris was piled up on the beaches and the river delta. With advance warning of the flood flow coming down the creeks, the level of the Cuyamaca Reservoir had been lowered by some one billion gallons. Even with this release, the water level at the spillways was four feet deep and the reservoir filled to within 14 inches of the top of the dam. However, very little damage was received by this system.

5.128 The Sweetwater Reservoir dam was topped at 2:20 a.m. on 27 January, and by 4:30 the flow over this dam was 3.5 feet deep. At this time, 50 feet of an earth-filled dike north of the dam was topped and the dike washed away, forming a break 75 feet long and 30 feet below the parapet of the dam (Figure 24). The flood flow then by-passed the dam and inundated the valley from the dam to San Diego Bay. (Figures 25, 26).

5.129 Rainfall data for the month of January 1916 is given on Figure 27.

5.130 On the same day, water in the Lower Otay Reservoir rose rapidly and the outlet gate was opened. However, the inflow into the reservoir was greater than the outlet gate was capable of discharging and men were dispatched to warn the valley inhabitants that the dam would fail during the night. Most people heeded the warning and took to higher ground. At 4:45 a.m. water reached the top of the dam and by 4:50 was running down its downstream face. The dam destruction was very rapid and the reservoir emptied in 2 1/2 hours, with a huge wave estimated at between six and 20 feet in height, rushing 10 miles down the Otay Valley in 48 minutes. Areas of the valley which had been covered with brush were stripped to bedrock by the force of the water; damage in this valley was very high.

5.131 The number of deaths in San Diego County rose to 22, most of which were attributed to the Lower Otay Dam failure. Damages were estimated to be approximately $4.5 million. Practically all important railway and highway bridges in the county were either washed out or rendered useless (Figures 28a, 28b, 29, 30) and for nearly a month all supplies had to be brought into the City of San Diego by ship. Every bridge across the San Diego River was destroyed (Figure 26). All telephone and telegraph lines were out of service leaving radio as the only means of communication. Most water supplies were interrupted. Large acreages of land were left unfit for cultivation; many have never been cultivated since.

5.132 Beginning in the 1950's the former cultivated farm lands in the river bottoms were rezoned and subsequent urbanization took place. Today the flood plains are occupied by freeways, business complexes, shopping malls, condominums, townhouses and in one case a racetrack and golf courses.

5.133 The crest discharges of streams in southern California for January, 1916 are given on figures 31 and 32.

5.134 Between 1916 and 1938, no major floods occurred in the southern California region except for the flood of January 1, 1934 at La Canada Valley (Troxell and others, 1942).

5.135 Minor floods, however, did occur in certain areas of southern California in 1918: 1921-22; 1926; 1927; 1931; 1932; 1934; 1936 and 1937.

Figure 24. View across lateral break in Sweetwater Dam in January 1916 (photograph from U.S. Geological Survey).

Figure 25. View of auto and wagon bridge across San Diego River just prior to collapse in January 1916 (photograph from U.S. Geological Survey).

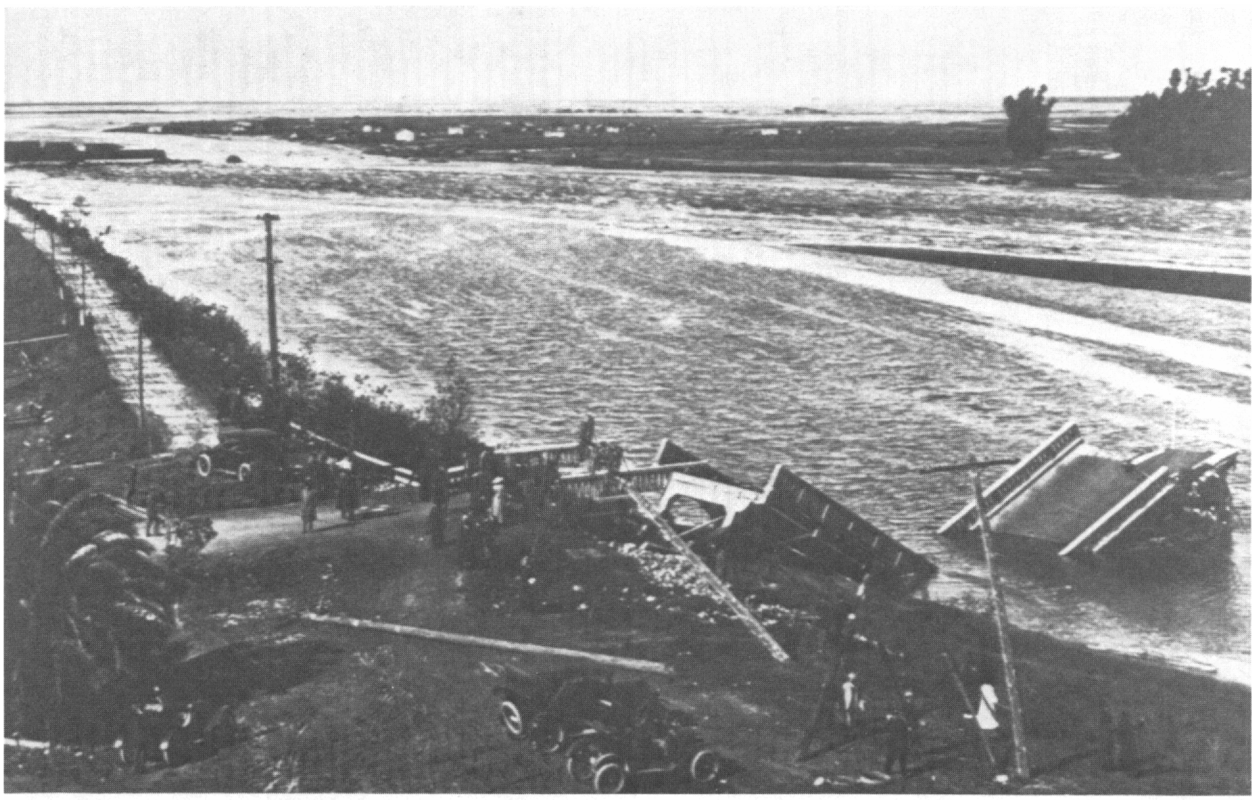


Figure 26. View looking west at bridge across San Diego River (Fig. 25) destroyed during flood in January 1916. All bridges across the San Diego River were destroyed during this flood (photograph from U.S. Geological Survey).

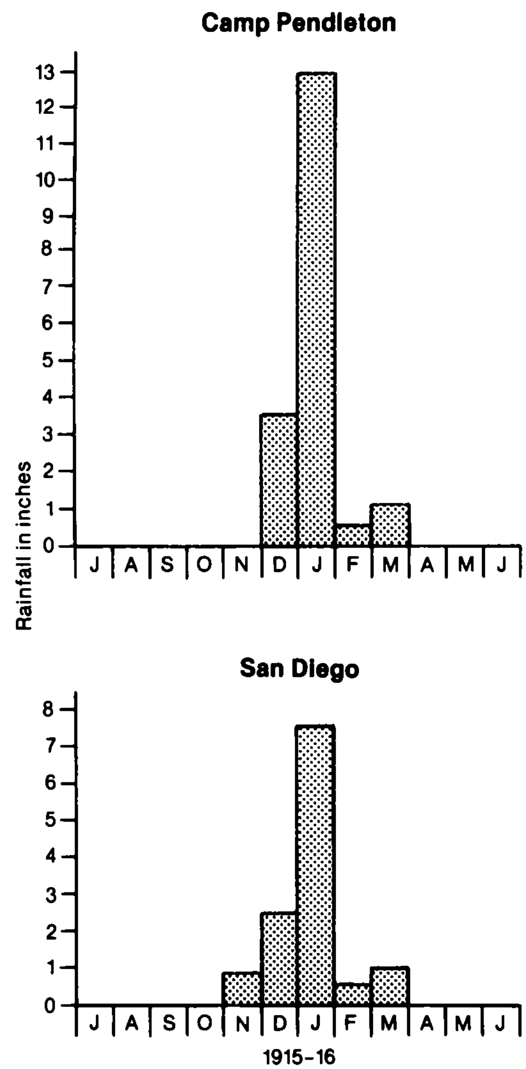


Figure 27. Rainfall at San Diego and Camp Pendleton for the great flood year of 1915-1916. An amount of 12.55" of rain fell at San Diego and 18.10" at Camp Pendleton. Note: 8" fell at San Diego in a period of a week as did more than 10" at Pendleton (data from Hydrology Section, County of San Diego).

Figure 28A. View looking up Deluz Canyon near Fallbrook in 1915, just prior to the 1916 flood (photograph from U.S. Geological Survey).

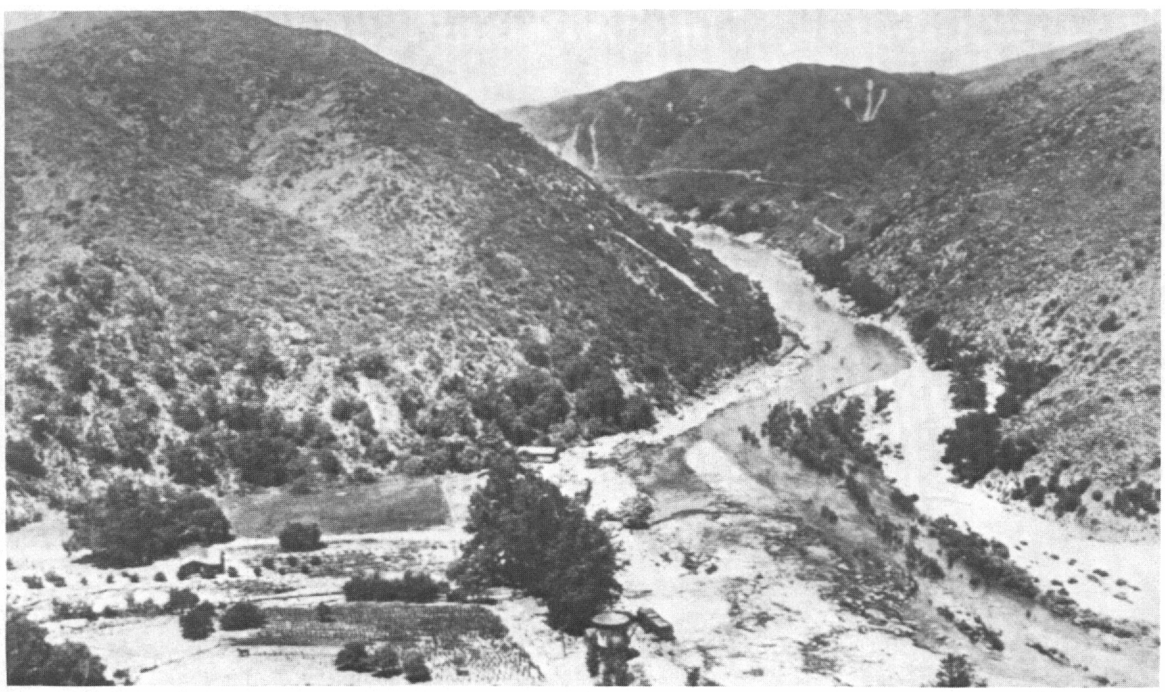


Figure 28B. View from same location as Fig. 28A in January 1916. Railway roadbed and bridges across the canyon were destroyed. Also note the occurrence of new landslides near the back of this photograph (photography from U.S. Geological Survey).

Figure 29. View looking north across San Luis Rey River in flood stage, January 1916 (photograph from U.S. Geological Survey).

Figure 30. View along the beach at Oceanside, January 1916. Wood and debris on beach came from denudation of inland wooded areas (photograph from U.S. Geological Survey).

Station.	Date.	Time.	Gage height (feet).	Drainage area (square miles).	Discharge.	Run-off per square mile.
Cottonwood Creek at Morena reservoir.	Jan. 27	4-6 p. m.		120	15,356	128
Otay River at Lower Otay reservoir.	...do...			98.6	[a] 25,500	238
Jamul Creek near Otay	...do...			69.8	18,100	259
Sweetwater River near Descanso.	...do...			43.7	9,870	226
Sweetwater River near Dehesa.	...do...			112	24,295	217
Sweetwater River at Rudolph ranch.	...do...			135	27,530	204
Sweetwater River near Jamacho.	...do...			172	43,002	250
Sweetwater River at Sweetwater reservoir.	...do...	4.30-5.30 p. m.		181	45,500	251
San Diego River at diverting dam.	Jan. 18	6 a. m.		102	4,710	46
Do	Jan. 28	6 p. m.		102	15,800	155
San Diego River at Capitan Grande dam site.	Jan. 27			189	[b] 36,300	192
San Diego River near Santee.	...do...		25.1	375	70,200	187
San Diego River at San Diego.	...do...	7 p. m.		431	75,000	173
Boulder Creek at Cuyamaca reservoir.	...do...	6 p. m.		12	2,393	199
San Vicente Creek at mouth.	...do...			74.9	18,600	248
Switzer Canyon at San Diego.	...do...	7 a. m.		3.55	668	188
Santa Ysabel Creek near Mesa Grande.	Jan. 17			53.4	10,600	199
Do	Jan. 27	Noon	11.0	53.4	21,100	395
Santa Ysabel Creek near Ramona.	Jan. 17	9 p. m.		110	14,300	130
Do	Jan. 27	7 p. m.		110	28,400	258
San Dieguito River at Carroll dam site.	...do...	1-3 p. m.	21.2	299	72,100	241
Santa Maria Creek near Ramona.	...do...	5 p. m.	15.9	57.3	7,140	125
San Luis Rey River near Mesa Grande.	Jan. 17	1.15 p. m.	12.8	209	24,400	117
Do	Jan. 27	1.30 p. m.	18.0	209	58,600	280
San Luis Rey River near Pala.	...do...		18.1	322	75,000	233
San Luis Rey River at Oceanside.	Jan. 17			565	40,000	71
Do	Jan. 27	9.30 p. m.		565	95,600	169
Santa Ana River near Mentone.	Jan. 17			189	29,100	154
Santa Ana River at San Bernardino.	...do...				40,000	
Lytle Creek at San Bernardino.	Jan. 18	9.00 a. m.			10,000	
San Jacinto River near San Jacinto.				108	30,000	278
San Jacinto River near Elsinore.	Jan. 28	11 a. m.	19.0	717	14,000	195
South Fork of San Jacinto River at Hemet reservoir.	Jan. 27	4 p. m.		65.8	9,550	145
San Gabriel River near Azusa.	Jan. 18	7 a. m.	12.0	222	40,000	180
Los Angeles River at Los Angeles.					7,208	
Los Angeles River near Dominguez Junction.					31,113	
Arroyo Seco near Pasadena.	Jan. 17	9.30 a. m.	9.3	16.4	3,150	192
Arroyo Seco at Los Angeles.					6,215	
Sespe Creek near Sespe.	Jan. 17		18.7	216	18,000	

[a] Reported by George Cromwell, city engineer, San Diego. (See Engineering News, vol. 75, No. 15, p. 718.)

[b] Mean of two estimates computed from cross sections and slope data.

Figure 31. Crest discharges, in second-feet, of streams in southern California for January 1916 (from McGlashan and Ebert 1918).

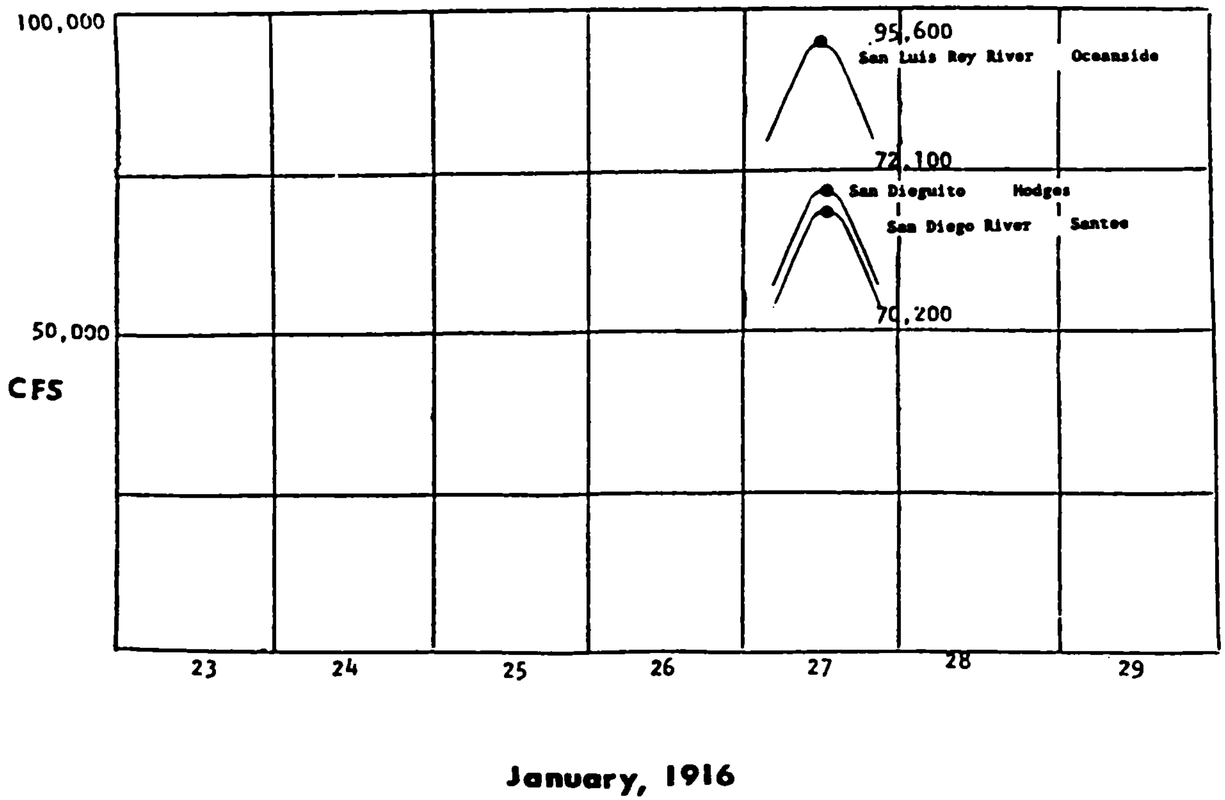


Figure 32. Graph of crest discharges on select San Diego County rivers during the great flood January, 1916. (data from Hydrology Section County of San Diego, 1976).

5.136 The flooding in 1938 and again in 1941 was even more damaging but these more recent floods were not as severe as the 1916 flood and not nearly as serious as those in the 1880's (Kuhn and Shepard, 1984).

Storm Year: 1921-1922

5.137 Rainfall for the year 1921-1922 was concentrated along the coastline as well as the mountains during December 1921 and January 1922 (Figure 33). Minor flooding occurred along with coastal erosion at selected areas. River discharge for December 1921 is shown on figure 34.

Years: 1922-1933

5.138 These years were primarily drought years; annual rainfall rates were below normal. Lynch (1931) states:

> "In 1922 there was high water with very large run-offs, but no flood of consequence. Since 1922 have been nine seasons, almost all of them below normal [as of 1931].
>
> The severity of this period is about comparable to that between 1781 and 1810, but that drought was of much greater duration than has been this one to the present time."

5.139 During this period at Los Angeles the drought was not as severe as was the one between 1821 and 1832, nor the one from 1897 to 1904 (Lynch, 1931).

Storm Year: 1927

5.140 This was another year of heavy rainfall flooding (Figure 35). Rainfall is given on figure 36, and river discarge data is shown on figure 37. San Diego County (1976) stated:

> "The rainfall intensity and totals of the 1927 storm are considered similar to those of the 1916 storm and yet, the flood peak was but half as large. One reason behind this fact may be that the ground cover throughout the drainage basins was more dense, as there had been no major forest fires since 1917. In addition trees, heavy brush and many structures scoured away during the 1916 flood had not had time to grow back or be restored; therefore, the streams flowed more freely than in 1916. There are very few detailed records available for this storm, but the damage estimate was $117,000 (1927 evaluation)."

Wet Period: 1934-1945

5.141 These years comprised the most recent wet period, according to Ganus (1975) who based his conclusions on tree ring data. During this period above normal rainfall was recorded annually (County of San Diego Rainfall records)

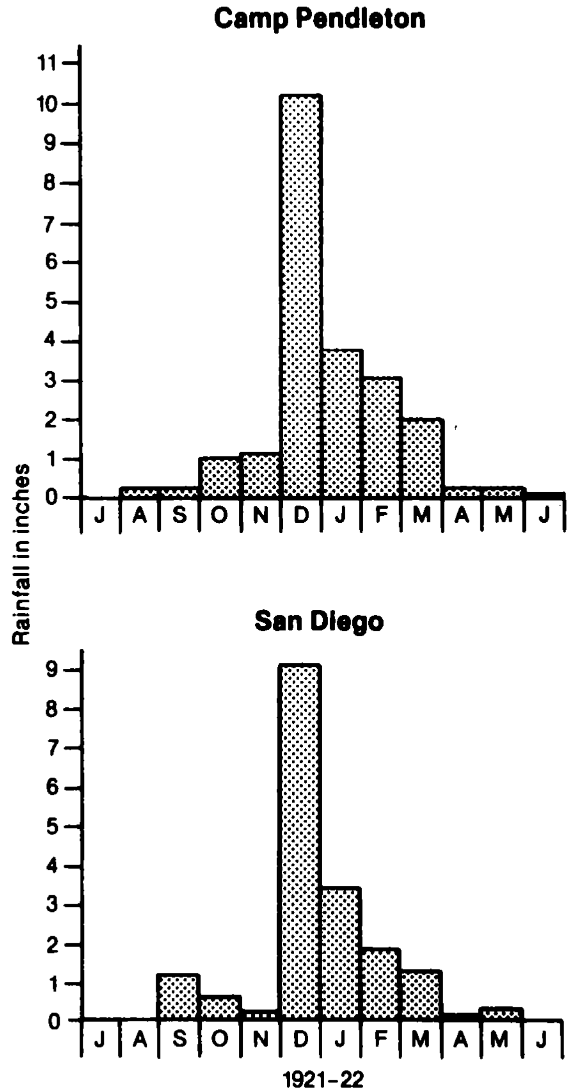


Figure 33. Rainfall at San Diego and Camp Pendleton for water year 1921-1922. Rainfall at San Diego amounted to 18.65" while 21.81" of rain fell at Pendleton. The rainfall was extremely concentrated at both locations (data from Hydrology Section, County of San Diego).

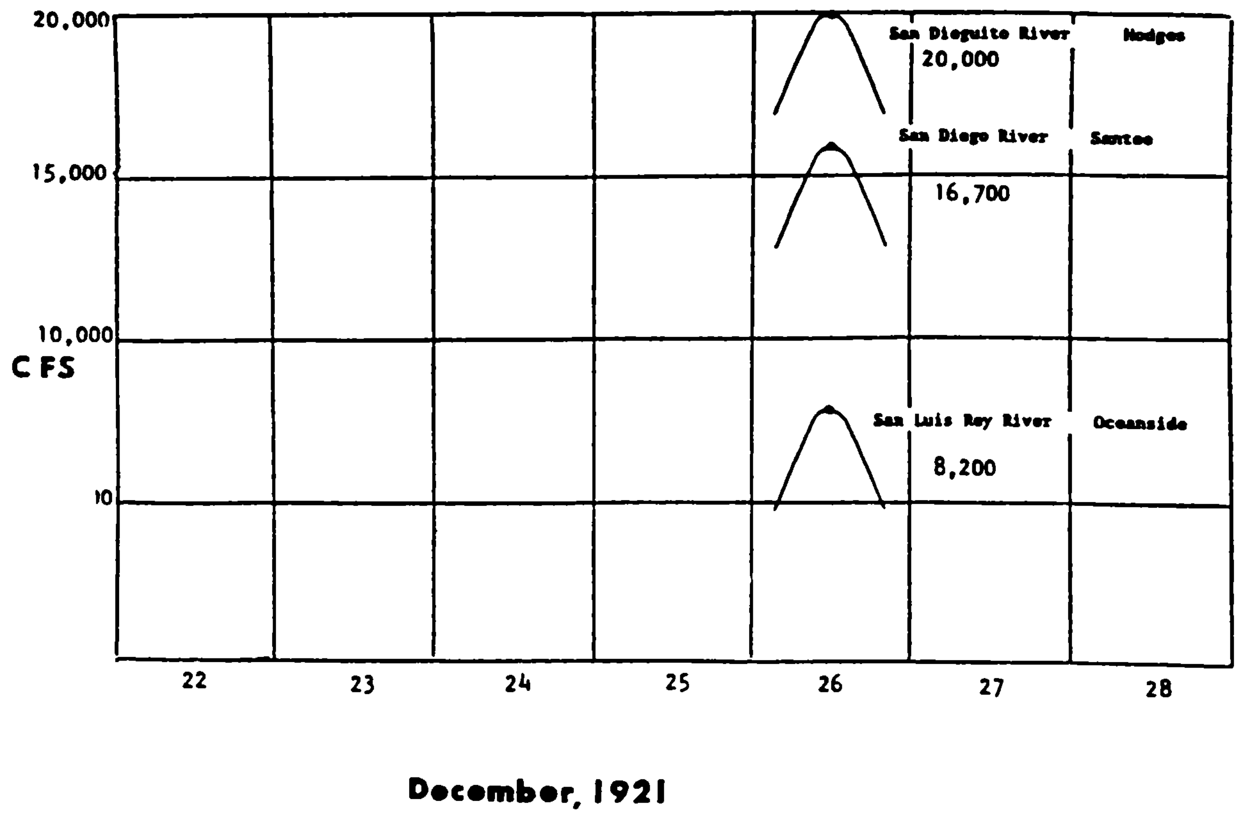


Figure 34. Graph of crest discharges on select San Diego County rivers during the minor flood of 1921-22 (data from Hydrology Section, County of San Diego, 1976).

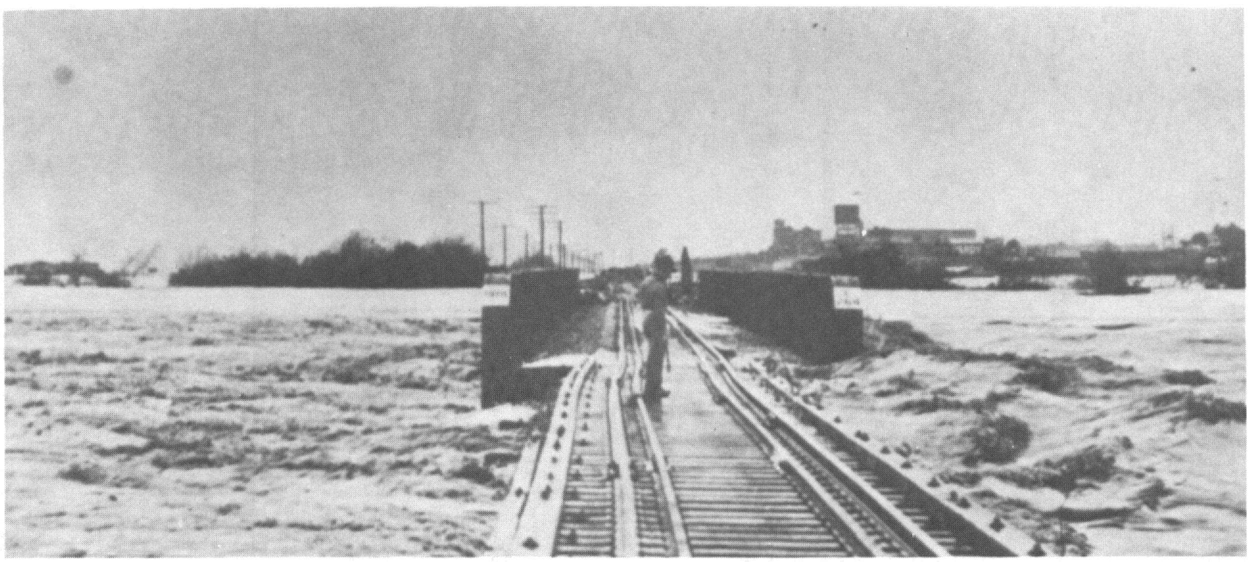


Figure 35. View of the 1927 flood on the San Diego River. Runoff from a series of back-to-back storms flooded Mission Valley, threatening to destroy the Santa Fe Railroad bridge. Note: 6.5" of rain fell at San Diego and 28" at Cuyamaca Lake between 13-17 February (photograph from Pourade, 1965).

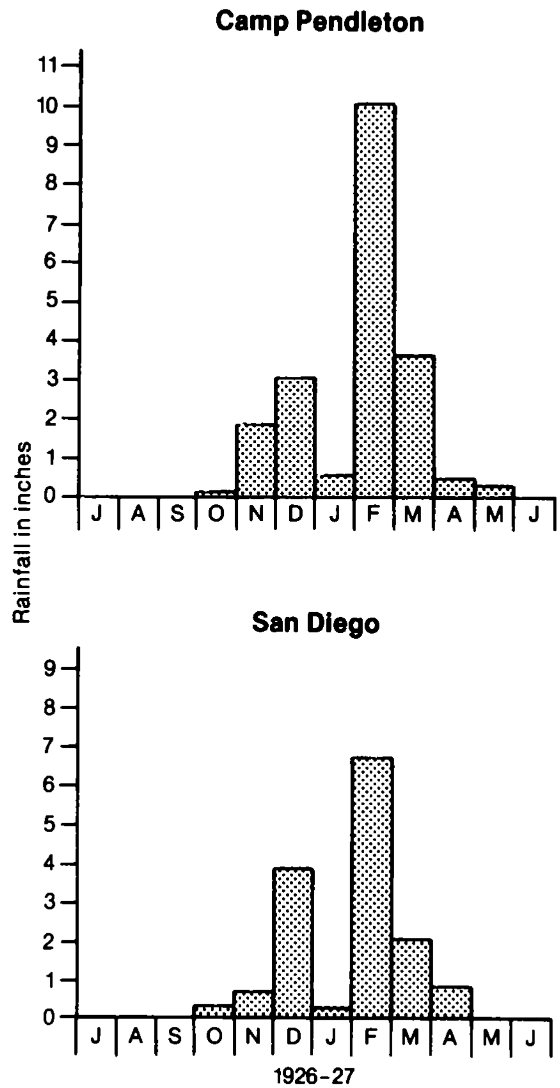


Figure 36. Rainfall at San Diego and Camp Pendleton during the water year 1926-1927. An amount of 14.74" of rain fell at San Diego while 20.32" fell at Camp Pendleton. Most of the rain fell in a very short period of time on saturated ground in February 1927 (data from Hydrology Section, County of San Diego).

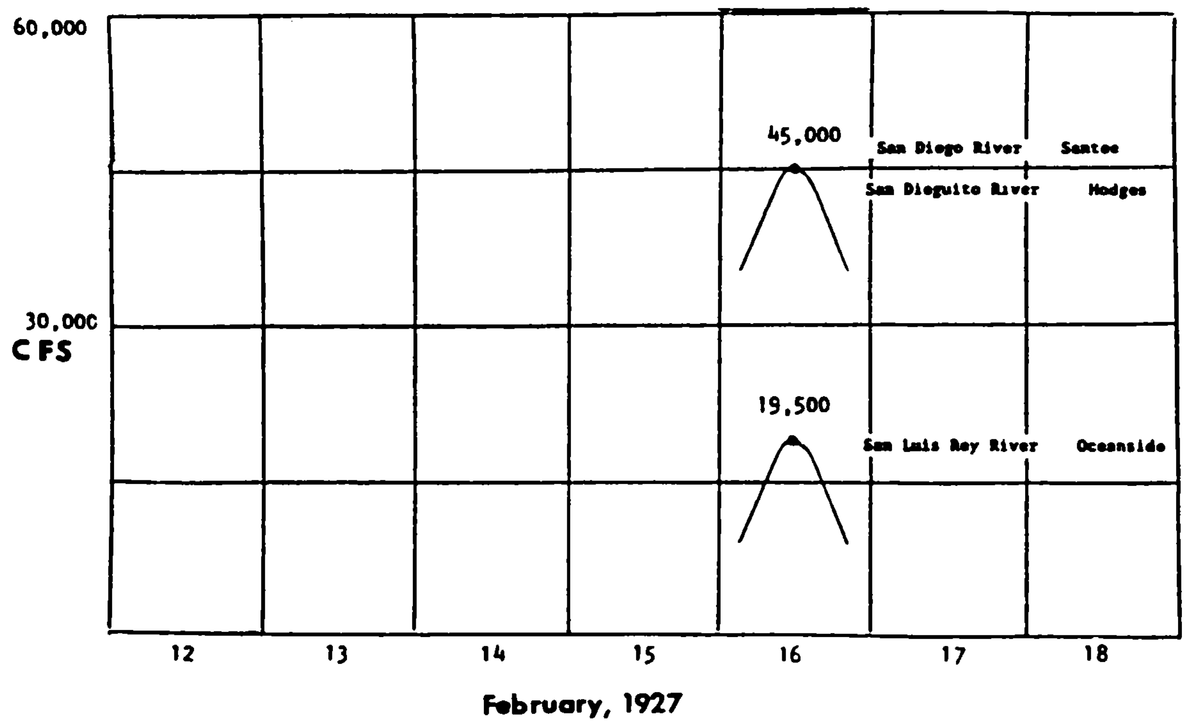


Figure 37. Graph of crest discharges of select San Diego County rivers during the flood of February 1927 (data from Hydrology Section, County of San Diego Report, 1976).

and some exceptionally strong storms occurred, both from the north and tropical storms from the south (Figure 38).

Storm Year: 1934

5.142 Severe destructive sea storms occurred during this period (Kuhn and Shepard 1984). However, inland flooding was not as severe as was reported in past years. A flood in January 1934, however, did great damage in La Canada Valley in Los Angeles County. Troxell and Peterson (1937) reported that:

> "In La Canada Valley there was a reported property damage exceeding $5,000,000, including 400 houses demolished or rendered uninhabitable, and more than 40 lives were lost. Streets, highways, and yards were strewn with wreckage and debris; automobiles and garages were rolled and piled in a conglomerate mass; bridges were destroyed; culverts and drains were clogged. The flood ravage was concentrated in the La Canada and Glendale areas to a much greater degree than elsewhere in this foothill region.
>
> The flood was caused by a 3-day storm that began moderately on the afternoon of December 30, 1933, and increased in intensity on the following day. Rainfall records indicate that the heaviest precipitation occurred over an area of intermediate altitude (ranging from about 1,000 to 3,000 feet) extending inland from Santa Monica to Claremont, a distance of about 50 miles. An earlier storm, on December 14 and 15, when about 4 inches of rain fell, undoubtedly had considerable effect in preparing conditions favorable to a high rate of run-off from the storm that continued through December 31 and January 1."

5.143 During the summer of 1934 large storm waves more than 30 feet in height from a southern-hemisphere storm caused significant damage to coastal areas from Laguna Beach to Santa Barbara (McEuen, 1935). Actually there were large swells beginning 21-25 August and 4-7 September 1934.

5.144 McEuen (1935) reported: "There was a recurrence of destructive waves from September 4 to 7, centering northward in the Long Beach area. Relatively little effect was noticed at San Pedro and Santa Monica. A mile of the Santa Fe tracks on the shore a the town of San Clemente, thirty miles south of Laguna, was washed out. Newport Beach and Balboa suffered even greater damage than during August, and further damage, threatened at Malibu by the battering waves, was averted by means of temporary embankments of sand bags. A long stretch of fence in front of homes there was washed out the night before. Parts of the Roosevelt highway along the coast of Malibu were covered by surf".

5.145 At Newport Beach, high waves carried away six electric light poles. Several blocks of summer homes in west Newport remained perched unsteadily above the surf on slender piles, and a great quantity of the beach sand was

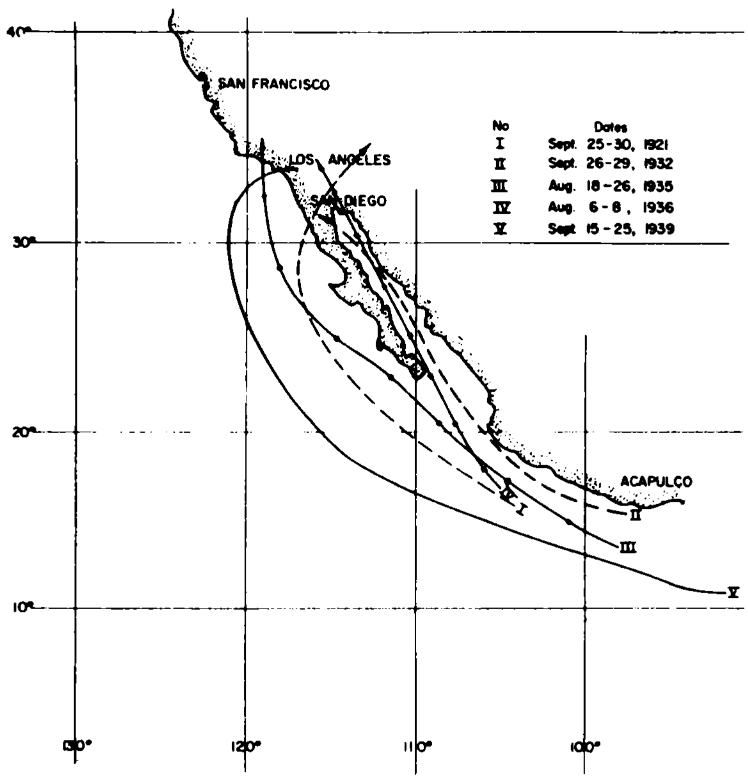


Figure 38. Tropical cyclones of the eastern Northern Pacific which caused damage along the southern California coast. Note the concentration of damaging storms during the 1930's (from U.S. Army Corps of Engineers, 1960).

washed from underneath. Two houses and a garage were carried out to sea and wrecked, and passage of Pacific Electric trains was hampered near Newport by undermining of the tracks in some places".

5.146 At Long Beach, the five-hundred-foot wooden Pine Avenue pier was destroyed on September 5, filling the areas with wreckage, and endangered other nearby structures.

5.147 Between the 7th and 12th of December, 1934 huge waves again were reported at Newport-Beach that were said to have been even more destructive than those of August. At Santa Monica, two large openings were made through the rockmount breakwater. McEuen (1935) indicated:

> "That the force of the waves was sufficient to displace very heavy granite rocks, many weighing thousands of pounds, and some several tons."

Winter: 1936-1937

5.148 Minor flooding occurred during February 1937 (Figures 39, 40). The floods of 1937 resulted from a storm that struck the coast near the San Luis Rey River but decreased as it moved southward (County of San Diego, 1976).

Record Flood: 1938

5.149 The floods of March 1938 were extremely severe in southern California (Troxell and others, 1942), and the flood runoff from the storm of March 1938 was exceptionally heavy in the main streams crossing the valley floors and in the larger streams in the mountains.

5.150 The origin of the storm was briefly described in a report of the U.S. Army Corps of Engineers (1938):

> "The storm, or rather series of storms which caused the flood of March, 1938, originated in Siberia, circled Southward over the Pacific Ocean to Midway Island, swinging eastward near Hawaii, and thence to the Pacific Coast. In their long, encircling course over the Pacific Ocean, a great amount of moisture was absorbed. Reaching southern California, the air masses swept in at high speed at almost right angles to the main mountain ranges. As the moist air was thrust upward by these obstructions, it encountered the colder upper air. The rapid condensation resulting caused excessively heavy rainfall."

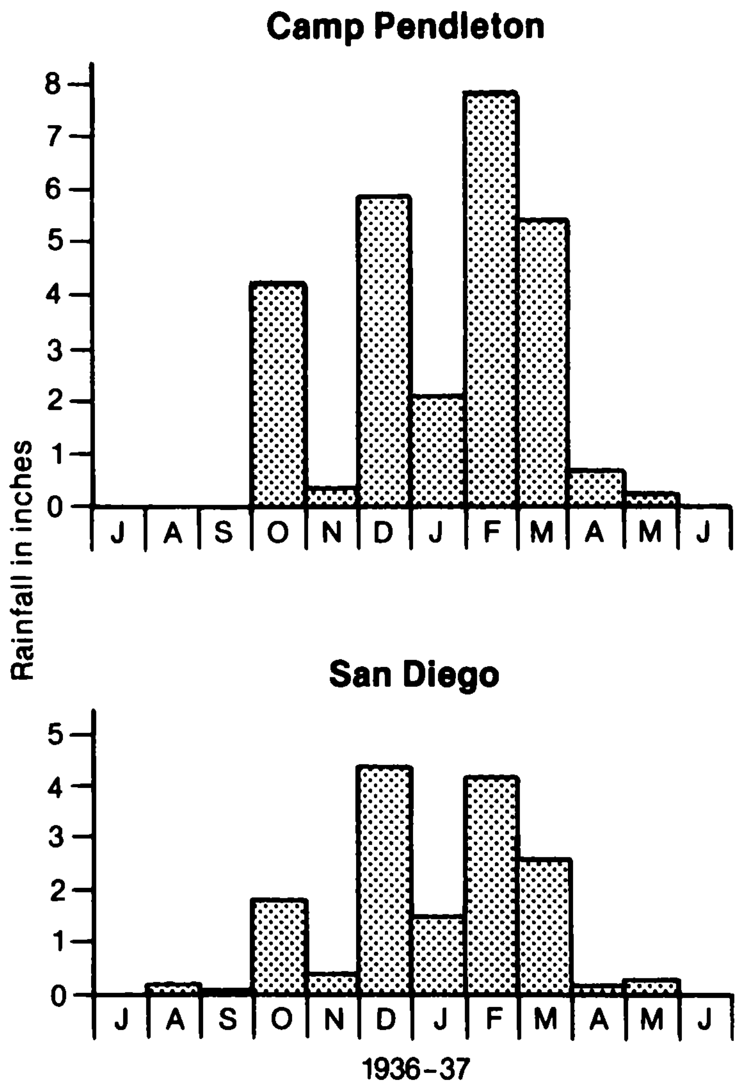


Figure 39. Rainfall at San Diego and Camp Pendleton for water year 1936-1937. At San Diego 15.93" of rain fell while at Camp Pendleton 27.05" of rain were recorded (data from Hydrology Section, County of San Diego).

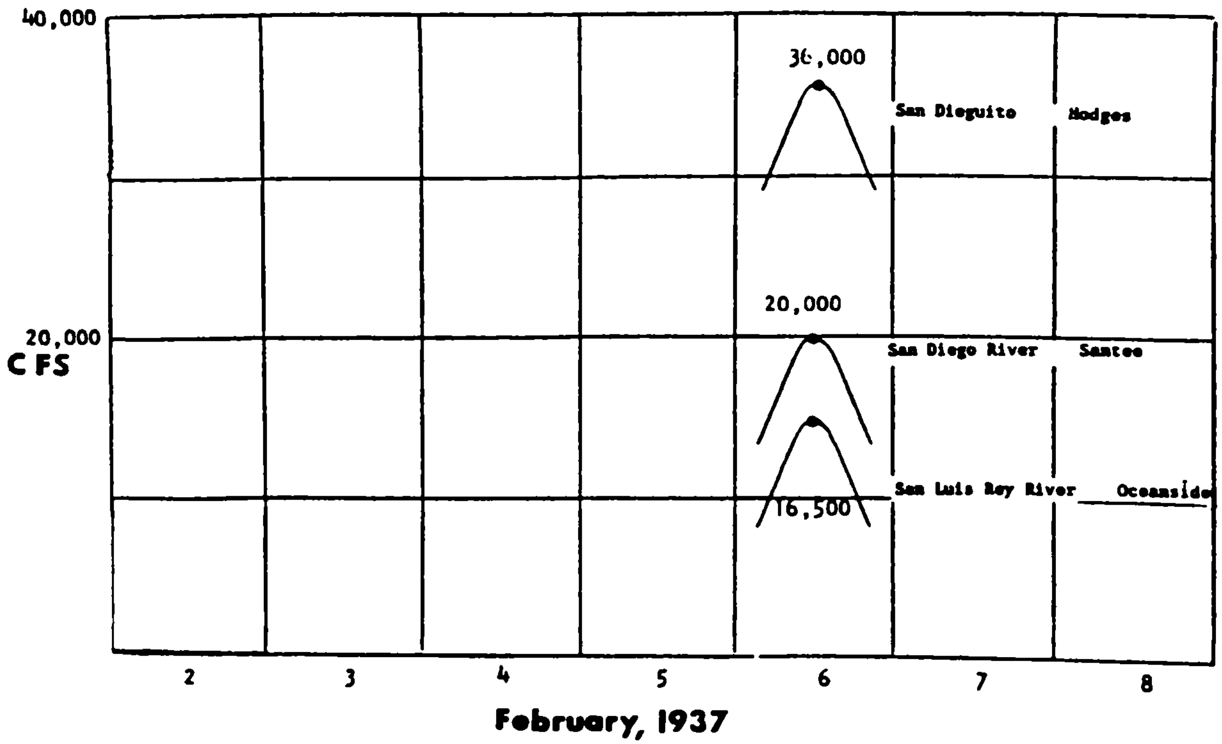


Figure 40. Graph of crest discharges along select San Diego County rivers during the flood of February 1937 (from Hydrology Section, County of San Diego, 1976).

5.151 Ziebauer (1966) also reported on this period:

> "In March 1938, following antecedent rains, a series of storms, the greatest in 70 years, lashed the region from San Luis Obispo to San Diego to cause an estimated property damage of over 78 million dollars and a loss of 87 lives. Records indicated runoff of more than 1000 cfs/sq. mi. and debris flows of 70 acre-feet per mile."

5.152 In San Diego County the flood of 1938 caused damages estimated at $600,000 and caused considerable reservoir sedimentation (County of San Diego, 1976) See figure 41 for rainfall at San Diego and Camp Pendleton and figure 42 for river discharge data.

5.153 A complete, well documented account of the 1938 flooding and subsequent damage is found in Troxell and others (1942) entitled "Floods in March 1938 in Southern California", U.S. Geological Survey Water-Supply paper No. 844.

Record Tropical Storm of 1939

5.154 In September, 1939, great storm and wave damage occurred along the southern California coastline due to a tropical storm. The San Pedro-Long Beach area was particularly hard hit (Horrer, 1950).

5.155 Nicholson and others (1946) examined reports of unusual waves between 1899 and 1946 that were reported along southern California and indicated that for:

> "Over a period of forty years only one typhoon, that of September, 1939, entered Southern California waters with very high wind velocities and caused significant damage due to wind waves."

5.156 Marine Advisors (1960) made a study for the Corps of Engineers of wave conditions at Oceanside at the time additional harbor entrance structures were being designed to accommodate the Oceanside recreational harbor. They examined daily historical weather maps and newspapers for storm damage that had occurred between 1891 and 1958, and found fifty storms that occurred during the period of time. The Marine Advisors report of 1960 indicated that for all storms investigated, the tropical storm of 24-25 September, 1939 created the most severe wave conditions.

5.157 The tropical storm of September 24-25, 1939, which generated the most severe waves over a 50-year period, approached from the southeast and the breakers had heights greater than 24 ft (7.3 m) at Oceanside (Horrer, 1950). Marine Advisors (1960) further state that the most severe winter storm waves during the period studied approached from a westerly direction and created breakers having a height exceeding 17 ft (5.2 m). They describe the September 1939 storm in the following paragraphs:

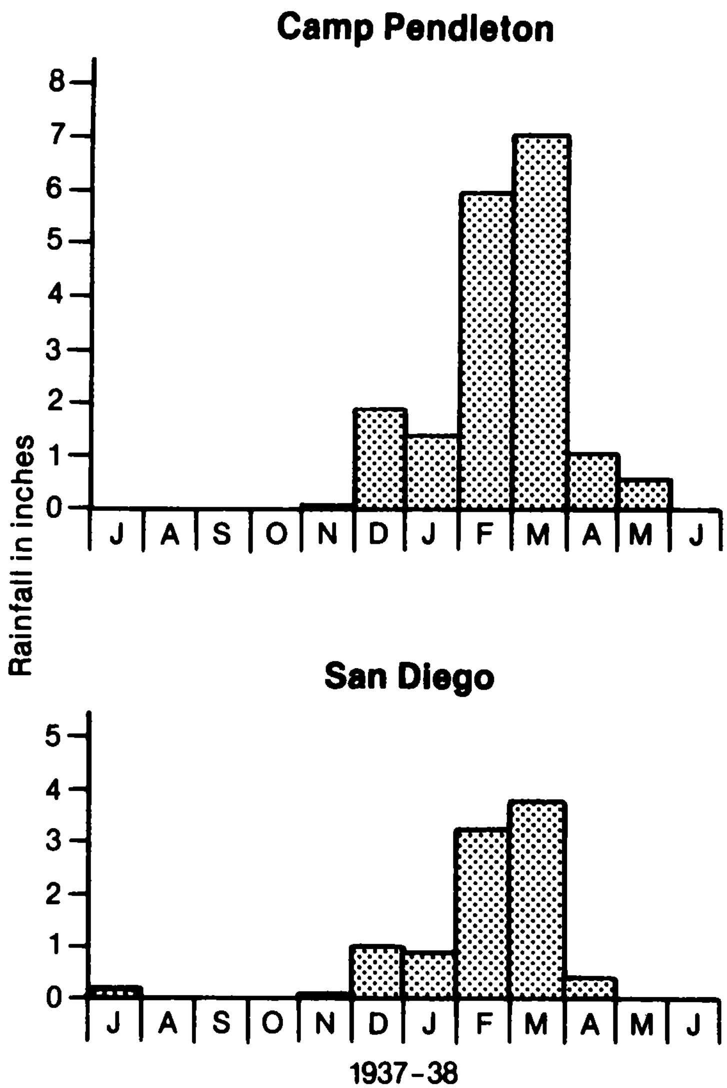


Figure 41. Rainfall at San Diego and Camp Pendleton during the water year 1937-1938. An amount of 9.72" of rain fell at San Diego and 18.53" fell at Pendleton, but the rain was very concentrated temporally falling on already saturated soil (data from Hydrology Section, County of San Diego).

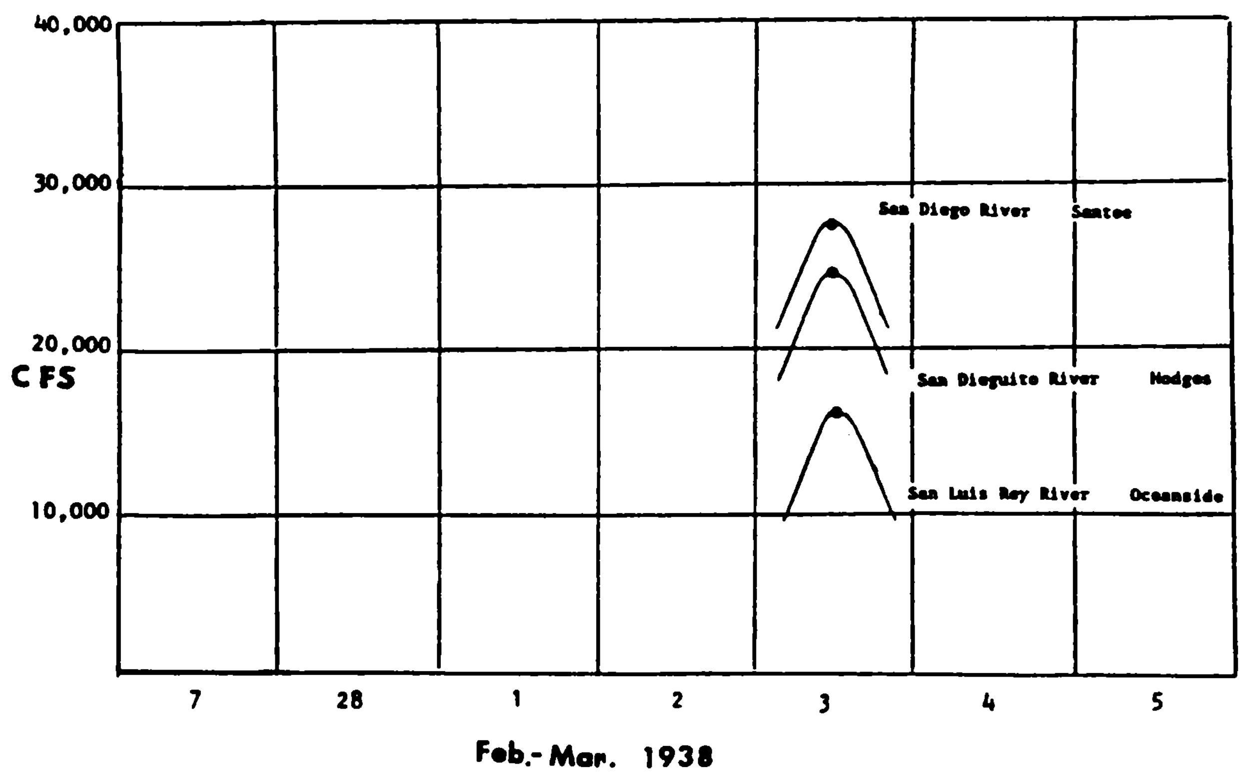


Figure 42. Graph of crest discharges along select San Diego County rivers during the flood of February-March, 1938 (from Hydrology Section, County of San Diego, 1976).

September 15-25, 1939 - Severity and Damage Reports:

5.158 "This is the only tropical storm recorded that caused wave and wind damage in the southern California coastal area. it was first sighted off Central America at 11 degrees N, 92 degrees W on Sept. 15. It travelled west-northwest at about 200 miles per day until on or about the 20th. It commenced to curve northward and then move up along the coast of Baja California. Early Sept. 22 winds in the northeast quadrant of the storm, of interest to our study, were 500-1000 miles from the Oceanside area. Subsequently, the storm moved toward the north and dissipated at the mainland near Santa Monica Bay early on the 25th.

5.159 This storm is one of the worst from the standpoint of winds, and certainly it is the worst from the standpoint of waves, that ever occurred in southern California during the 59 years of records and maps examined. The U.S. aircraft carriers Enterprise and Lexington obtained hourly records of weather information in the area of the Los Angeles-Long Beach outer harbor, and maximum wind recorded by them was 50 kts. Their wave observations were given only according to state of sea classification. One of the carriers recorded that waves had reached the 12 to 20 foot range; the other indicated 20 to 40 foot height.

5.160 Newspapers reported 65 lives lost at sea off southern California, and coastal damage was estimated at greater than $1,000,000. Persons ashore estimated swell heights at 30 feet, and ships at sea reported 45 foot waves in the Catalina Channel. At Point Mugu floods and turbulent seas ripped away bridges and roads. The seas tore away half of San Clemente's 1,200 foot long pier. Newport and Balboa pier centers collapsed. The storm loosened foundations of many houses along the coast, particularly at Alamitos Bay and Sunset Beach. At Long Beach considerable damage was done to the outer breakwater in which stones above mean sea level that weighed two to 20 tons were dislodged. This is one of the two cases on record [of storms] that materially damaged this particular breakwater; the other case was southern hemisphere swell in April, 1930".

September 1939: Fetches, Wind and Hindcasted Waves

5.161 "The center of this storm moved from the eastern tropical Pacific along a path roughly paralleling the west coast of Mexico until it reached the area between 25° and 30° latitude, at which time it began to curve inland towards the Los Angeles area. By 0430 PST on 23 September the storm had reached a position such that wave trains were developing which would be felt along the southern California coast, but it was not until about 24 hours later that it began to generate the train from 205° which produced the highest significant wave. This wave reached the forecast area with a height of 25.9 feet and period of 13.7 seconds at 0530 on the 25th. Build-up to this height had been rather rapid at first, with a leveling-off three or four hours before maximum height and a gradual decline afterwards. Representative values are: 18.4 feet, 12.8 seconds at 1600 on the 24th; 24.2 feet, 13.6 seconds at 2330; 25.9 feet, 13.7 seconds at 0530 on the 25th; 24.25 feet, 13.1 seconds at 1300.

5.162 Rainfall for 1939-1940 at San Diego and Camp Pendleton is given on figure 43 and storm tracks of tropical depressions for the period are given on figure 44. As noted by the U.S. Weather Bureau in Hydrometeorological Report No. 37 (1962):

5.163 "This was a violent storm in its early offshore history. On the morning of September 22, while west of the southern tip of Baja California, winds of 60 knots and barometer 971 mb were reported near its center. Its offshore track from that point was parallel to the coast. This track was made possible by a strong ridge over the western United States and another offshore, separated by an elongated inverted trough extending along the coast both at the surface and aloft. This trough persisted from the 19th through the 23rd, resulting in extremely high coastal and coastal mountain temperatures in Southern and Central California.

5.164 By the 24th, the ridge over the west had weakened, allowing the storm to veer toward NNE and then toward northeast as it approached the Southern California coast. Windspeed at San Pedro reached 37 knots before the 998-mb Low center entered the coast in that vicinity about 0800 PST on the morning of the 25th. Damage in the area was estimated at $1,500,000, largely from wave action at the coast."

5.165 On the 24th of September 1939, an intense thunderstorm dropped 6.45 inches of precipitation in 6 hours at Indio, California. This intense thunderstorm occurred as moisture from the storm off the coast traveled northward through the Gulf of California and entered the Imperial Valley of California (Pyke, 1975a).

Storm Year of Record: 1940-1941

5.166 1940-41 was a very stormy and wet year during which flooding occurred. During the period between December 23, 1940 and January 7, 1941 a documented series of storms produced 30-ft deep water swell which, when coupled with high tides and heavy rainfall, caused severe damage along the southern California coastline (Kuhn and Shepard, 1979).

Early Indications of the 1940-1941 Storms

5.167 The forerunner of the storm of late December 1940 was observed by Shepard (Kuhn and Shepard, 1979) while coming up the coast of Baja California on the schooner E.W. Scripps with a group of scientists from Scripps Institution of Oceanography. Roger Revelle, U.S. Grant IV, and Francis Shepard found that the swell coming from a distant storm was so high that it was necessary to climb the mast to eye height above troughs from 30 to 35 feet before they could see over the top of the largest wave. When they arrived in San Diego on December 23rd, the storm already had hit the coast and Revelle found the beach cliff had eroded 18 feet in front of his home at La Jolla, necessitating the immediate introduction of large boulders (riprap) to stop the erosion. Shepard had to leave for the east on the 24th so was unable to make any further observations of storm damage until returning in June of 1941.

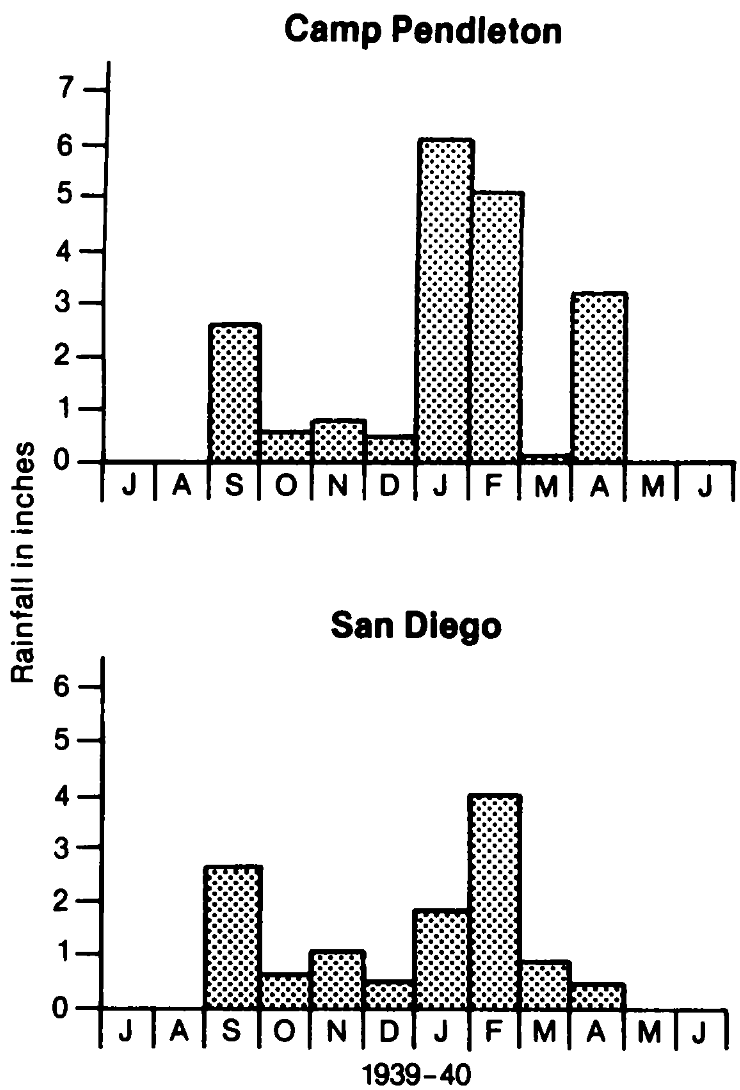


Figure 43. Rainfall at San Diego and Camp Pendleton for water year 1939-1940. At San Diego 11.30" of rain were recorded and 18.84" at Camp Pendleton. Note: Rainfall for September 1939, the month of the great tropical storm (data from Hydrology Section, County of San Diego).

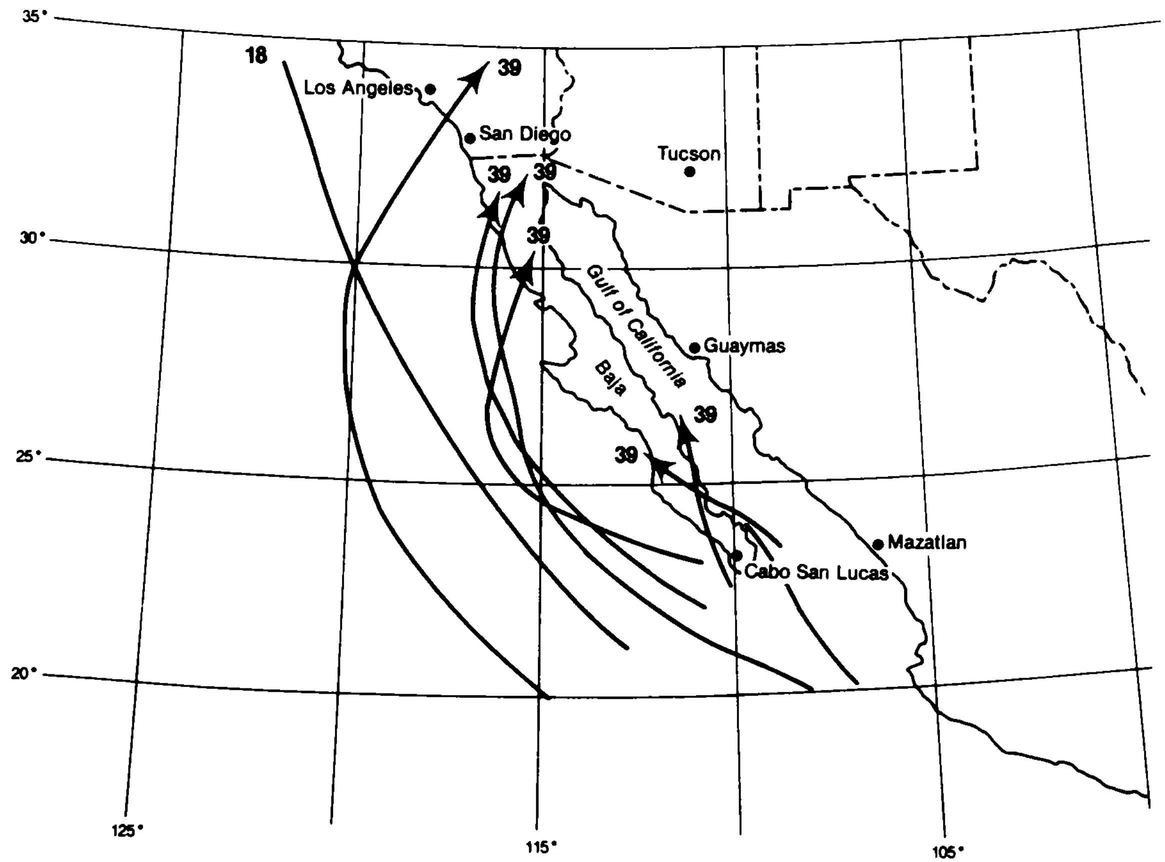


Figure 44. Years of tracks of major tropical storms which entered the southern California area (adapted from Douglas, 1973).

Storm Reports

5.168 Based on the compilation of newspaper clippings, eye-witness accounts, photographs taken at the time, Santa Fe Railroads records, Weather Bureau data and logs of ships, it is possible to qualitatively document the nature of this 1940 storm period. We will present this sequentially with emphasis placed on the damage that occurred between Los Angeles and San Diego.

23 December 1940

5.169 Beginning on 23 December 1940, coastal communities from Canada to Mexico reported damage as a result of huge breakers smashing directly on buildings, structures and railroad beds (Kuhn and Shepard, 1979). In Oregon, the barometer plunged to the lowest since the early 1900's. Landslides and flooding were reported from San Francisco south through Santa Barbara (San Diego Union, 24 December 1940).

San Diego County

5.170 At San Diego, the 23rd of December, 1940 was the wettest December 23rd on record with 2.05 inches of rain falling in 16 hrs., 2.91 inches of rain fell in 3 hrs., and 2.25 inches fell in Escondido during a 4 hour period.

San Francisco [24 December 1940, S.D. Union]

5.171 Storm from Pacific Ocean Broke with gale-force winds.

1. Heavy flooding of railroad and highways; endangered shipping.
2. New storm hovering over the Pacific might bring more heavy rain.
3. Northern California and Pacific Northwest hardest hit.
    a. Portland, Oregon
    b. Santa Cruz, California -- 4.24" in 48 hours (6 city blocks inundated by floods)
    c. Santa Barbara -- slides and flooding delayed trains.
    d. Palm Springs flooded.

Three storms were reported to be generating:

1. Over western Oregon and Washington,
2. one centered south of Dutch Harbor and, Alaska.

Oregon [24 December 1940, S.D. Union]

5.172 Huge breakers battered Oregon coastline:

1. Lowest barometer reading since 1914.
2. Wind whipped a scheduled 8' tide into an 11' tide.

San Diego County [25 December 1940, S. D. Union]

5.173 Extremely heavy warm rainfall continued in San Diego County with the heaviest gale winds reported in Escondido in 25 years, and torrential rains at Camp Pendleton and San Onofre with more than 6 inches falling between the 23rd and 24th December (Figure 45). The storm brought 7 billion gallons of water to the reservoirs in the county.

San Francisco [Date occurred 12/24/1940]

5.174
1. 45 to 65 mph winds (gale force)
   Hailstorms
   Thunderstorms

2. Unusually high tides broke over levee 1000 feet long protecting lower San Francisco Bay, inundating 30 acres east of Bayshore Highway.

Palm Springs [25 December 1940, S. D. Union]

5.175
1. 4" rain from storm;
   1,000-pound boulders block Union Pacific train tracks.

San Diego County [26 December 1940, S. D. Union]

5.176 Oceanside reported pounding seas from San Luis Rey River south. At Wisconsin Street, El Sereno Court was severely damaged by beach cobbles with many foundations of homes being undermined. Note: Prior to this storm a very wide beach existed along Oceanside with sediment most recently (at that time) deposited as deltas at the mouths of the Santa Margarita and San Luis Rivers during and following the 1938 floods.

Redondo Beach [26 December 1940, S. D. Union]

5.177 Battered by 30-ft waves.
Residences were undermined and sections of the Strand were destroyed by 30 ft. combers that battered the shoreline.

San Diego County [27 December 1940, S. D. Union]

Ocean Beach

5.178 City rushes rock bulwark to break force of waves.

1. 7.1 high tide, 20 ft waves smash over Mission Beach, hurled concrete benches into lots and against homes. Toppled one house at Ocean Beach, threatened others along the ocean front.

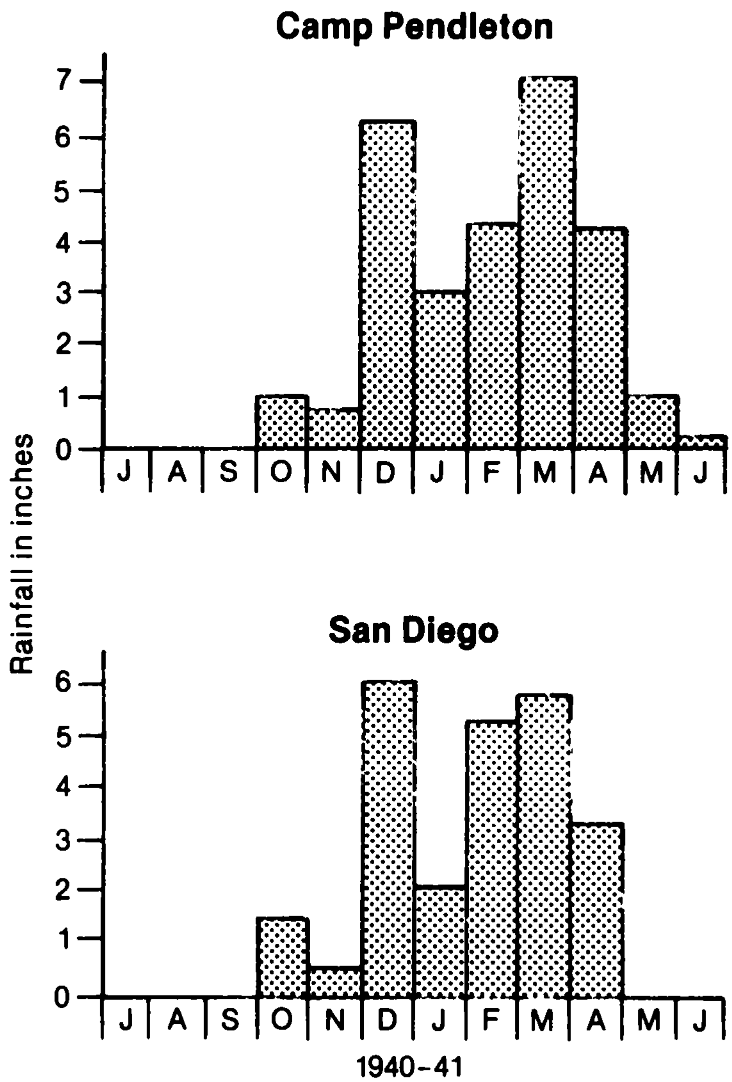


Figure 45. Rainfall at San Diego and Camp Pendleton for water year 1940-41. At San Diego 24.74" of rain were recorded while at Pendleton 27.88" of rain fell (data from Hydrology Section, County of San Diego).

2. 500 tons of rock were places south of the Mission Beach seawall to break the force of the waves which sent water surging over Mission Blvd. into the Bay.

3. 7.3 ft. high tides expected for next few days.

4. Ocean Beach danger greatest. 1,000 sandbags were filled and stacked to prevent surf from undermining foundations of homes.

   Five houses in danger at Saratoga Avenue; one house toppled into water.

<u>La Jolla</u> [27 December 1940, S. D. Union]

5.179 Rocks and debris thrown up on streets at La Jolla Hermosa. La Jolla Blvd. covered with sand and debris. Many 400-pound boulders were loosened by rains, roared down canyons and smashed against houses with terrific force.

<u>Redondo Beach</u> [27 December 1940, S. D. Union]

5.180 1. Two houses and 5 blocks of ocean front walk collapsed today.

2. 3-story bathhouse and a dozen residences were threatened by 25-ft breakers that pounded the shoreline today.

3. Twelve or 15 homes were being undermined by the attack of the big waves, heightened by unusually heavy ground swells.

4. One homeowner had his house dragged to higher ground in order to save it.

<u>Long Beach</u> [27 December 1940, S. D. Union]

5.181 City engineers worked to prevent the Belmont Peninsula on which 70 homes are built from being cut off from the mainland. Waves swept over the bulkhead and damaged some homes.

<u>Venice</u> [27 December 1940, S. D. Union]

5.182 Several homes undermined and boardwalks were washed out along a 1-mile stretch.

<u>San Pedro, Point Fermin</u> [27 December 1940, S. D. Union]

5.183 A 6-acre bluff which has been slipping toward the ocean in recent years made a new move and additional cracks several feet in width were opened.

Port San Luis [27 December 1940, S. D. Union]

5.184 Sixty feet of railroad rack was washed out. The Union Oil Co.'s cold storage building was undermined.

South of Santa Barbara [27 December 1940, S. D. Union]

5.185 Long sections of beach land were washed away, threatened cottages, waves swept over Highway 101. At Sandyland, cottages were threatened when their supports were destroyed.

5.186 A new storm was reported approaching the southern Calfornia coast on the highest tides of the year. An emergency conference of all southern California mayors was proposed because of the great damage that was occurring at this time.

San Diego County [28 December 1940, S. D. Union]

Mission Beach

5.187 Tons of kelp was lifted by waves high over seawalls and strewn along Mission Beach. The kelp will be removed as soon as crews get the sand and rocks cleared off the streets.

Los Angeles County [28 December 1940, S. D. Union]

Redondo Beach

5.188 The battering 25-foot high combers undermined a house and liquor store normally 50 ft from the water at high tide. Both collapsed.

Two houses which topped into the ocean on the 27th, today were being smashed to pieces.

A 3-story bathhouse was taking a severe hammering and the owner was planning immediate construction of a $25,000 bulkhead to protect it.

San Francisco [28 December 1940, S. D. Union]

5.189 Coastline had experienced 2 weeks of solid rain. Many schooners disabled by storm. Several vessels severely damaged off the Hawaiian Islands. New storm reported 700 miles southwest of San Diego.

5.190 A lull in the storms occurred on 29 December 1940 in San Diego County.

31 December 1940

5.191 At Del Mar in San Diego County, a railroad freight train collapsed to the beach as a result of the hammering of the cliff face by the extremely large storm swell coinciding with the perigean spring tides and sediment saturation of the bluff top. A seawall located on the bluff face collapsed from the top down, (Figure 46), (Kuhn and Shepard, 1979, 1984).

5.192 These storms ended by 7 January 1941.

5.193 As a result of the same and subsequent storms, considerable destruction took place in Encinitas. In 1938 the Self-Realization Fellowship had built a temple about 35 feet from the bluff edge; (Figure 47a) in 1942, after the bluff had been weakened by the combination of heavy rains and pounding surf, the temple fell over the edge was destroyed (Figure 47b), (Kuhn and Shepard, 1984).

5.194 Apparently the same storm greatly modified the beach cliffs that extend from south of Torrey Pines State Park to the north of La Jolla. Prior to the storms, a long talus slope allowed access from a precipitous walled canyon in the beach cliff to the beach below. After the storm this area, which was visited in the spring of 1941, had become a vertical canyon, left hanging by the removal of the talus. It seems certain that this was the result of the storm period at the end of December 1940. It took about 25 years before this talus rebuilt, allowing easy access into the canyon, but the access lasted only for a few decade before the stormy winter of 1977-78 again cut away the fill (Kuhn and Shepard, 1979).

5.195 The meteorological conditions for the significant stormy winter of 1940-41 are described by Pyke (1972):

> "During the greater winter season of 1940-1941 a pattern of warm and moderately heavy storms also prevailed in California; and because of the persistent recurrence of these storms, some all-time high rainfall year (July-June) totals of precipitation were recorded. This entire rainfall season was characterized by a very vigorous mid-latitude flow pattern across the north Pacific, with many prominent short wave ridges and troughs. In addition, a large number of cyclones during that season split off from the main band of westerlies and were diverted southeastward toward the southern California coast by blocking highs which built up over and off the coast western Canada". Pyke (1972) went on to note that:
>
> "The 1940-1941 season, in contrast to the other periods of warm, west-southwesterly type storminess, occurred during the climax of an extremely prominent equatorial Pacific Ocean warm period--one of the greatest in oceanographic history".

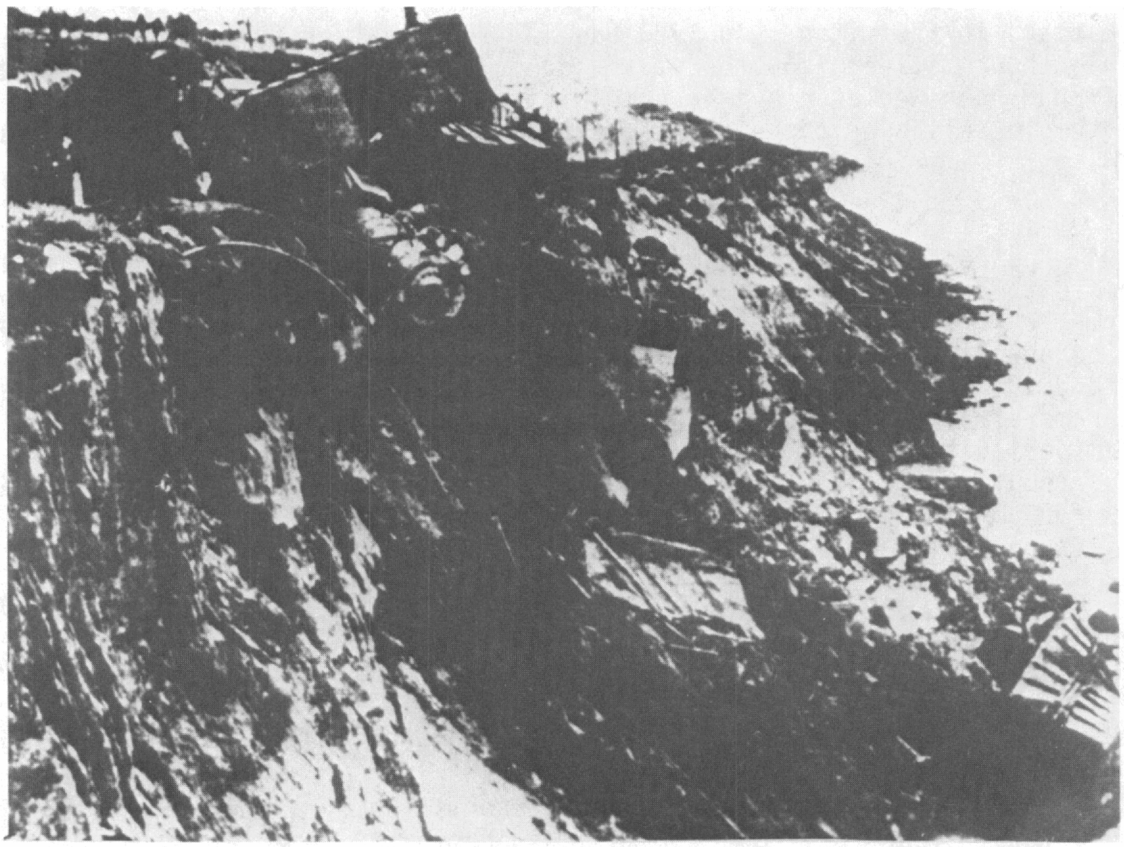


Figure 46. January 1941 view of train which collapsed to the beach at 8th Street in Del Mar (photograph from San Diego Union, January 3, 1941).

Figure 47a. Oblique aerial view of Self Realization Fellowship temple at Encinitas in 1938 (photograph courtesy of Self Realization Fellowship).

Figure 47b. View of temple collapse in the early 1940's following significant sea storms accompanied by saturation of the bluff top (photograph courtesy of Self Realization Fellowship).

5.196 No other severe storms such as 1940-1941 occurred in southern California but there were wet years between 1941 and 1947.

Great Storm and Flood Years -- A Comparison

5.197 Of the many floods which have occurred in southern California, and specifically in San Diego County since 1850, very few qualify as "great" floods. The most severe of the floods which occurred between 1850 and 1987 were in the years 1861-1862, 1867, 1884, 1889, 1891, 1914 and 1916.

5.198 It becomes apparent that each drainage basin must be considered individually with respect to intensity of rainfall, surface runoff, recent periods of vegetation burn-off, and flooding, (Kuhn and Shepard, 1984).

1861-1862: "The Noachian Deluge"

5.199 As mentioned in a previous section, the flood of 1862 was regionally more severe and caused greater devastation than any other flood since the coming of the missionary fathers. It affected an area between British Columbia southward through Baja California. Professor William Brewer (Farquhar, 1966) stated that as of January 31, 1861 in California alone:

> "It is supposed that over one-fourth of all the taxable property of the State [California] has been destroyed."

5.200 Because of this flood, the 1884 to 1891 floods and 1914, and especially 1916, a comparison of all historial floods was initiated by the United States Geological Survey and subsequently was published in the Water Supply Paper No. 426 (1918). The following data is taken directly from that publication.

5.201 The U.S. Geological Survey (McGlashan and Ebert, 1918) initially compared the magnitude of the floods.

Basis of Comparison

5.202 "To determine whether the flood of 1916 was more or less severe than previous floods in southern California, a search was made of the early records, and many old residents of the country were interviewed. The results of this work are summarized in the following pages. Of particular interest is the record of wet and dry years, compiled by Mr. A. Campbell, who has lived in San Diego County since 1869. Information as to conditions in most of the years prior to 1840 was taken from records of the Mission Fathers."

Tia Juana River

5.203 "Information concerning early floods on Tia Juana River was also furnished by Mr. Campbell, who considers the flood of 1884 the greatest in total run-off that has occurred during this time. The peak of that flood, however, was not so great as the peaks of the floods of 1891 and 1916, the only years in which, since 1869, water from Tia Juana River overflowed into the Otay drainage basin. In February, 1891, snow was above the fences at Mr. Campbell's ranch in Laguna Mountain divide, and one drift was 21 feet deep. This snow melted during a five days' rain. The lower Tia Juana Valley was flooded about as much as 1891, when the large hotel at Hot Springs, Mexico, was washed away, as in 1916. In comparing these floods the effect of storage at Morena reservoir in 1916 should be considered."

Sweetwater River

5.204 Mr. C. H. Ellis, Sr., who has lived near Descanso for 35 years, states that the floods of 1884 and 1916 were the largest on Sweetwater River within that period. At the site of the Geological Survey gaging station the water rose 3 to 4 feet higher in 1916 than in 1884. In 1916 the channel was wider and at least 2 feet deeper than in 1884. It is his opinion that the flood of 1916 was approximately double that of 1884.

5.205 It is of interest to note that Mr. [William S.] Gregg considered the flood of 1895 greater than that of 1884. The record at Sweetwater Reservoir shows that the total run-off of Sweetwater River for the year ending June 30, 1895, was 73,412 acre-feet; the record of J. F. Covert, chief engineer, Sweetwater Water Co., shows that the run-off at Sweetwater Reservoir for January 16 to 31, 1916, was 111,000 acre-feet. . . . Mr. Covert gives the total run-off from October, 1915, to September, 1916, as 160,580 acre-feet.

San Diego River

5.206 The highest known discharge into Cuyamaca Reservoir, stated in terms of maximum rate of inflow for 24 hours, is as follows:

	Second-feet
1895, January 17	1,630
1906, March	1,120
1916, January 27	2,400

5.207 The following information was obtained in an interview with Mrs. Martha Swycaffer, who came to San Diego in 1854.

5.208 " Mrs. Swycaffer states that the flood of 1862 was greater than any other within her time. The rain began in the fall of 1861 and the rainy season lasted until June, 1862. Beginning Christmas Day, a rain set in which lasted for at least six weeks, during which time there was not sunshine enough to dry a handkerchief. At about the end of this storm the rain set in more heavily, causing the big flood.

5.209 Before the peak the river occupied two channels, one on each side of the Swycaffers' home but a considerable distance from it. The Swycaffer house was a two-story brick-veneered building. As the flood increased it was necessary to move into the upper story of the building, all the lower doors and windows being left open to ease the force of the flood. The Swycaffer house was the only one in the San Diego River bottom that stood, and all inhabitants in the vicinity sought refuge in the second story. The refugees were rescued from the second-story window in a surf boat manned by sailors, and Mrs. Swycaffer and three babies were then sheltered in an adobe house in Old Town. During the night a dike built for the protection of Old Town was overtopped, and her refuge was again flooded. The family was carried to the Old Palms and placed under the one which was out of water; the ground at the other was flooded.

5.210 The flood of 1862 was of long duration for a southern California stream, as it maintained approximately its peak height for 24 hours. Mrs. Swycaffer does not consider the flood of 1884 as large as that of 1916. In her opinion the flood of 1916 was next in magnitude to that of 1862.

5.211 Mrs. Swycaffer was familiar with what is now the Foster and Lakeside country. At Lakeside the high water reached to the old adobe ranch house, or an elevation of the present Lakeside store. At Foster the flood height reached nearly to the top of an immense oak, which was removed when the railway was built. This flood would have washed out all the present buildings in Foster. Previous to 1862 the present site of San Diego (New Town) was on rounded hills; the draws and gullies now existing were begun in 1862. When Mrs. Swycaffer first visited the Warner Hot Springs the springs broke out on a gradually sloping plain; the flood of 1862 made the topography as it is today.

5.212 Mrs. Swycaffer knew everyone in Old Town in 1862, and no flood within the memory of any or in the traditions of the place was comparable with it".

San Luis Rey River

5.213 " In the early days houses and ranch buildings were built on high ground, and the bottom lands along the river channels were used only as pastures. As the number of settlers increased, the agricultural lands became more valuable, and at the time of the floods of 1916 the bottom lands had reached a high state of cultivation and buildings were erected where they would be most convenient without any particular thought of the damage from excessive floods.

5.214 Mr. P. F. Hubbard, who has lived near San Luis Rey River since 1873, considers that the only flood in his time that is comparable higher at his well and the channel was wider than in 1884. The bottom lands in 1884 were covered with brush and trees and the channel did not cut much. As there were no cultivated fields or buildings in the path of the flood the damage was slight.

5.215 Mr. Edward Canterini, who has lived in San Luis Rey Valley since 1884, states that there was more rain in 1884 than in 1916 and the flood was of longer duration, but he does not consider that the maximum discharge was as great as in 1916. The river did not have a well-defined channel prior to 1891.

5.216 Immediately after the flood of January 27, 1916, Father Doyle, of the Pala Mission, San Diego County, talked with an old Indian who had lived along San Luis Rey River for many years. The Indian stated that this flood was greater than that of 1862. The old mission ditch at Pala, constructed more than 100 years ago, was washed out in a number of places by the flood of 1916, but previous floods had not injured it. Father Doyle considers the flood of 1916 the greatest which has occurred since the valley has been settled. The flood of 1862 he places second in size, and that of 1884, third".

5.217 Edward R. Bowen, in a paper on the San Luis Rey floods of January, 1916, says:

> "The entire San Luis Rey Valley was inundated, the stream extending from hill to hill--a distance of probably 1-1/2 miles--and covering an area of over 1,000 acres. The drift along the county road on the south side of the valley indicated a 6-foot depth of water at that point. It is probable that the enormous quantities of silt and debris carried by the stream in the first flood, together with that carried by the subsequent one, so built up and raised the old channel of the river that it was at a greater elevation than the adjacent valley lands. When the second flood came down this channel, its banks were overtopped and a new channel formed, cutting across the valley in a northeast to southwest direction, taking a long sweep to the westward at about the middle of the valley and returning to an old course near the narrows. All farms in the valleys of the lower river were completely destroyed and three people were drowned. The entire valley is covered wth deposit of sand and silt to an average depth of at least 3 feet, and in many places as much as 6 feet. Conditions along the upper river are not so bad. The valleys are more constricted and the stream better confined, although all crops along the bottom lands have been ruined."

Los Angeles and San Gabriel Rivers

5.218 "There were heavy floods on Los Angeles and San Gabriel Rivers in 1825, 1833, 1862, 1867, 1884, 1886, 1889 (2), 1890, 1911, and 1914, and it is said that serious floods occurred also in 1842, 1852, and 1874. From the testimony in the case of Andres Daneri v. Southern California Railroad Co., superior court of Los Angeles County, in 1897, the largest floods occurred in 1825 and 1833 and the next largest flood was in 1862. It seems to be generally agreed that the greatest flood since 1862 occurred in 1889. The flood table prepared by the United States Weather Bureau, for the period 1878 to 1914, shows that 41 floods occurred in the vicinity of Los Angeles during this period" (all quoted from McGlashan and Ebert (1918).

5.219 McGlashan (1921) also reported:

> "The flood of February 23, 1891, was not as large in the Los Angeles River as the previous flood of December, 1889, but in every stream east of the Los Angeles River it was much larger. This is due to the fact that the flood of December, 1889, was from heavy rainfall coming suddenly, while the flood of February 23, 1891, was due to accumulated snow, melted by the warm rain, having much less precipitation than the storm of 1889. This heavy snowfall was mostly wanting on the watershed of the Los Angeles River, which explains why the flood was so much less severe than on other streams lying farther east."

5.220 It is most important to note that no flood in the twentieth century compares regionally with those great floods which occurred prior to 1900.

Drainage Areas

5.221 A drainage basin comprises all the land that drains into a given stream. Drainage basins are generally named after the principal stream flowing into the ocean or bay.

5.222 There are seven major river basins and four major drainage groups in the San Diego Region. The river basins drain to the San Mateo Creek, Santa Margarita River, the San Luis Rey River, the San Diego River, the Sweetwater River, the Otay River, and the Tijuana River. The major drainage groups are the Laguna Hills group, the San Clemente group, the Escondido Creek group annd the San Diego group. The watershed areas are shown before dams were constructed on the upper reaches (Figure 48a) and after (Figure 48b).

5.223 As seen in figure 48b, the river basins are now substantially controlled, mainly by water-supply reservoirs. This is especially true of the basins to the south, which now have from 70 to 90 percent of their surface areas controlled (DMA Consulting Engineers, 1985, Table I).

5.224 The Laguna Hills Group drains from the southern end of the Santa Ana Mountains and Santa Margarita Mountains. The major subareas in this group include the San Juan Creek - Arroyo Trabuco basin, the San Mateo Creek basin, and San Onofre Creeks basin.

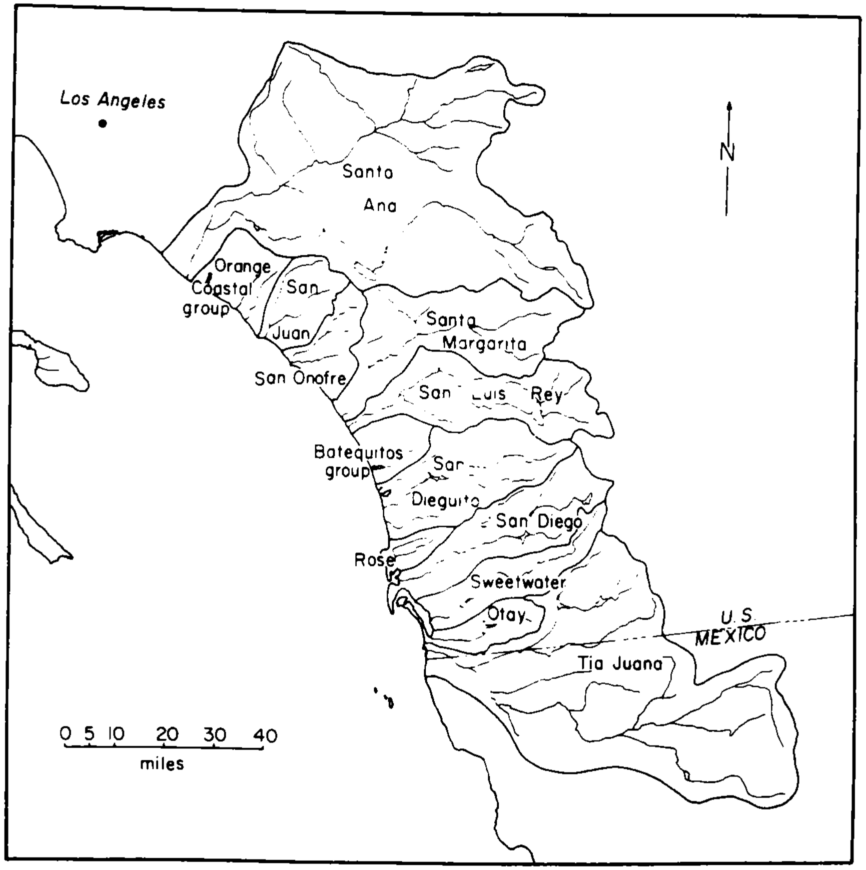


Figure 48a. Generalized coastal drainage basins in southeastern half of southern California (figure from Norris, 1964).

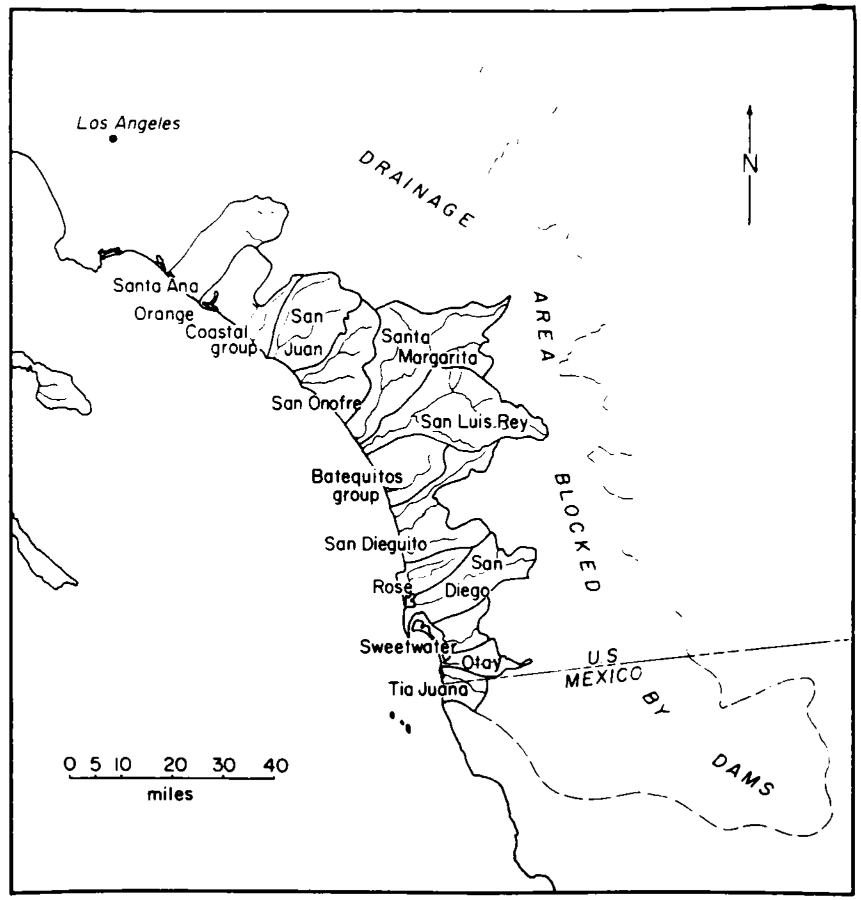


Figure 48b. Undammed or unobstructed portions of coastal drainage basins in the southeastern half of southern California (figure from Norris, 1964).

Table 1. Major control structures (from DMA Consulting Engineers, 1985).

Name	Watershed	Drainage Area mi^2	Year Completed	Remarks
O'Neill Lake	Fallbrook Cr (Santa Margarita R)	27	1885	
Skinner Res	Tucalota Cr (Santa Margarita R)	51.5	1973	
Vail Lake	Temecula Cr (Santa Margarita R)	306	1949	
Henshaw Lake	San Luis Rey R	207	1923	Also diverts to Lake Wohlford.
Lake Wohlford	Escondido Cr	8.0	1924	Water-supply and flood control.
Lake Hodges	San Diequito R	303	1919	Water-supply and flood control.
Sutherland Res	San Diequito R	54	1954	Upstream of Lake Hodges.
San Vicente Res	San Vincente Cr (San Diego R)	74.1	1943	Water-supply and flood control.
Murray Res	San Diego R	3.6	1918	
El Capitan	San Diego R	190	1934	Water-supply and flood control.
Cuyamaca Res	San Diego R	12	1887	Upstream of El Capitan.
Sweetwater Res	Sweetwater R	182	1888	Failed in 1916 flood.
Loveland Res	Sweetwater R	98	1945	Upstream of Sweetwater Res
Otay Res	Otay R	101	1919	
Barrett Lake	Cottonwood Cr	252	1922	Water-supply and flood control.
Lake Morena	Cottonwood Cr	114	1912	Water-supply and flood control.
Rodriguez Res	Tijuana R	976	1936	In Mexico.

5.225 The principal drainage basins in the San Diego County Western Watershed are as follows, from north to south [data from County of San Diego, 1976]:

<u>San Mateo Creek</u>

Area: 218 square miles--25% in Riverside County
10% in Orange County

Tributaries: San Onofre, Las Pulgas and Alison Creeks

Dams: None

Land Use: Military reservation, National Forest

Flood Damage: Roads, communications

<u>Santa Margarita River</u>

Area: 750 square miles--75% in Riverside County

Tributaries: De Lux, Temecula and Murrieta Creeks

Dams: None

Land Use: Military reservation

Flood Damage: Roads, cropland, communications

<u>San Luis Rey River</u>

Area: 565 square miles

Tributaries: Fallbrook Creek, Moosa Canyon and Pauma Creek

Dams: Lake Henshaw, Valley Center

Land Use: Rural, some urban in Bonsall, San Luis Rey, Oceanside

Flood Damage: Roads, crops, homes, utilities

Escondido Creek

Area: 211 square miles, including Buena Vista, San Marcos and Agua Hediona Creeks

Tributaries: Reidy Creek

Dams: Lake Wohlford, Dixon

Land Use: Rural--Escondido urban area mainly protected by flood control systems

Flood Damage: Roads, communications

San Dieguito River

Area: 350 square miles

Tributaries: Santa Ysabel, Santa Maria, Del Mar Creeks

Dams: Sutherland, Lake Hodges

Land Use: Rural--urban in Del Mar - race track/fairgrounds at Del Mar

Flood Damage: Roads, crops, fairgrounds, utilities

Los Penasquitos Creek

Area: 166 square miles, including Rose and San Clemente Canyons

Tributaries: Sorrento Creek, Carrol Canyon, Poway Creek

Dams: Miramar, Poway

Land Use: Rural--urban residential/commercial in Poway area and Sorrento Valley

Flood Damage: Extensive flooding in Poway, Sorrento Valley

San Diego River

Area: 483 square miles

Tributaries: Boulder, San Vicente, Alvarado, Los Coches and Forester Creeks; Sycamore, Murphy Canyons

Dams: Cuyamaca, El Captain, San Vicente, Murray, Padre

Land Use: Rural in uplands; extensive development in Lakeside, Santee and Mission Valley (San Diego) areas

Sweetwater River

Area: 242 square miles, including Chollas, Toyon Creeks

Tributaries: Peterson, Harbison, Spring Valley Creeks, Paradise Creek

Dams: Loveland, Sweetwater

Land Use: Rural in uplands; extensive development in lower reaches; crops

Flood Damage: Extensive residential/commerical in Chula Vista, National City, Bonita area; road, utilities, golf courses; industrial, docks, planned marina near San Diego Bay

Otay River

Area: 124 square miles

Tributaries: Janul Creek, Dulzura Creek, Poggi Canyon

Dams: Otay (lower and upper)

Land Use: Rural; same development in lower reaches, crops

Flood Damage: Roads, crops, utilities, salt ponds at San Diego Bay

Tijuana River

Area: 465 square miles in U.S.; approximately 1,860 square miles in Mexico

Tributaries: Pine Valley, Cottonwood, Campo, La Posta Creeks

Dams: Morena, Barrett, Rodriguez

Land Use: Rural--extensive development in Tijuana, Mexico. Channelization in progress in Mexico

Flood Damage: Roads, crops, utilities, lagoon area, extensive commercial and residential in Mexico

Littoral Cells

5.226 Emery (1960) and Inman and Chamberlain (1960) identified a series of littoral cells along the southern California coast. These cells are based on the concept of longshore transport of dominantly fluvially-derived sediment, which is entrapped either by submarine canyon heads or by points of land which extend seaward from the general position of the coastline. Three major coastal divisions are present in this study area. The Oceanside Littoral Cell extends from Dana Point to Point La Jolla, and this cell may be further subdivided by Carlsbad Submarine Canyon. The second division is the coastal lowland in the pacific and Mission Beach area, which occurs on the former delta of the San Diego River. Alluvium from the San Diego River extends almost to Crystal Pier at Pacific Beach, where it changes to a natural barrier (spit) extending across most of Mission Bay. The jetties constructed at the mouth of Mission Bay have interrupted the transport of sand from Mission Beach to Ocean Beach (Kuhn and Shepard, 1984), therefore, Ocean Beach is treated as a pocket beach in the present study. The coastal segment from the entrance to San Diego Bay to the United States-Mexico border comprises the Silver Strand Littoral Cell.

Littoral Segments: Dana Point to the United States-Mexico Border

5.227 Given the occurrence of the Oceanside, Mission Beach and Silver Strand littoral division (Figure 2), each may be subdivided into segments defined either by (1) distinctive mineralogic assemblages due to natural or man-influenced processes (especially beach nourishment programs), or (2) by known natural (lagoons) or man-made barriers (jetties and breakwaters) to littoral and transport. Osborne (1985) tentatively identified fourteen littoral segments using these criteria. It must be stressed that the petrologic data base used to define these segments is marginal. Eight of the fourteen segments identified consist of only one sample, which is usually associated with an apparent point source - either the mouth of a river or estuary or the side of one or more beach nourishment programs.

Oceanside Littoral Cell

5.228 The Oceanside Littoral Cell extends from Dana Point to the La Jolla Submarine Canyon, a distance of approximately 50 miles (FIgure 2). Most of the rivers within the cell have dams in their upper reaches (Table 1).

Recent Beach Nourishment

5.229 Dredging of coastal lagoons and harbors with subsequent deposition of the sediment on the local coastal beaches has occurred since the early 1940's. Between 1942 and 1947, the U.S. Army Corps of Engineers dredged two million cubic yards of sedimentary material from the Oceanside area (Shaw, 1980). For more detailed information on beach nourishment and emplacement on San Diego County beaches see Kuhn and Osborne (1987), tables 1-6.

Coastal Segments

5.230 For purposes of this study, the area from Dana Point to the Mexican Border is divided into the following geographic segments: (a) Dana Point to San Onofre Creek, (b) San Onofre Creek to Santa Margarita River, (c) Santa Margarita River to San Marcos Creek (Batiquitos Lagoon), (d) Batiquitos Lagoon to San Diequito River, (e) San Diequito River to Penasquitos Lagoon, (f) Penasquitos Lagoon to La Jolla Submarine Canyon, (g) La Jolla Coastal Segment, (h) Mission Beach Littoral Cell, (i) Point Loma Segment, and (j) Silver Strand Littoral Cell.

Dana Point to San Onofre Creek

5.231 Morphology. The Dana Point to San Onofre Creek segment, approximately 10 miles in length, consists of high bluffs separated from a narrow beach by a railway roadbed (Figure 49). San Mateo and San Onofre Creeks contribute sediment to beaches. Sand bars have formed across the mouths of the streams in storm years.

5.232 Coastal Changes. Erosion of the cliffs along Dana Point, Capistrano Beach, and San Clemente for the period studied has not contributed appreciable sediment to local beaches. The cliffs are physically separated from the beach by the railway roadbed which was constructed in the early 1880's and since that time has stopped cliffed-derived sediments from reaching the beach.

5.233 For this study, examination of the U.S. Coast and Geodetic Survey maps of 1885 and 1889 was compared with the most recent U.S. Geological Survey maps of 1947 and/or 1948. Little or no change along the base of cliff is perceptible when the early map is compared with the U.S. Geological Survey 1:24000 scale map.

5.234 The U.S. Army Corps of Engineers (1959) also indicated that:

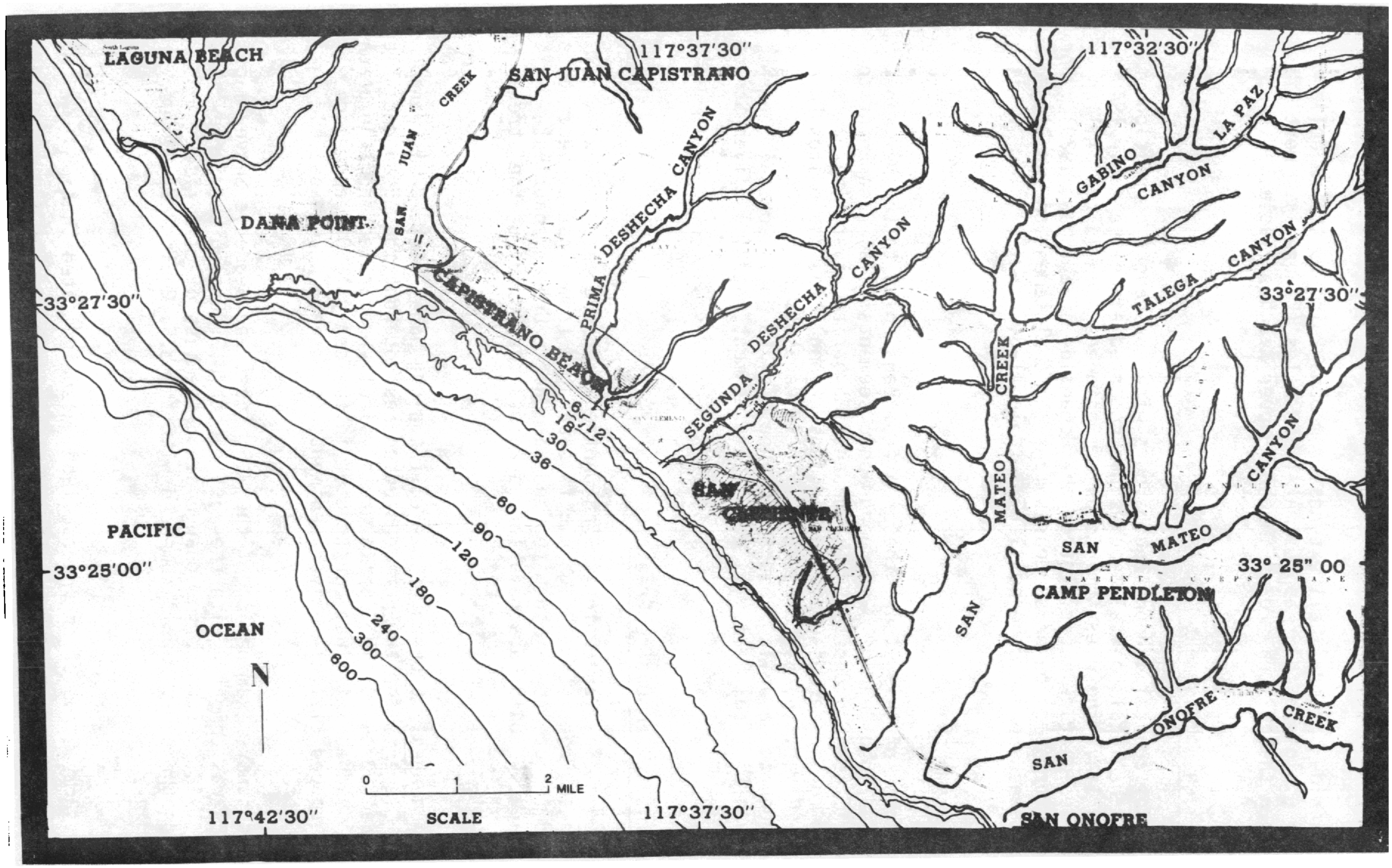


Figure 49. Location map of Dana Point south through Capistrano Beach, and San Clemente to San Onofre Creek. Note: Bathymetry in feet (from Kuhn and Shepard, 1984).

> "Examination of the Coast and Geodetic Survey field sheets in this area indicated that the bluff line between 1889 and 1934 had remained unchanged. All of the triangulation monuments set along the edge of the bluffs in 1933 were recovered in 1958."

5.235 Subaerial erosion is dominant over marine erosion along this segment of coast as a result of the location of the railroad which protects the cliff face from direct wave attack.

5.236 Subaerial erosion processes which affect these cliffs are the following 1) gullying of the bluff face as a result of heavy, rains which also saturate the sediments, initiating mudflows and landslides, 2) major stream incision, 3) and dissection of terrace surfaces.

5.237 Beach erosion locally has been very severe in years past in the San Clemente area with the railway roadbed being washed out in the 1930's and 1940's (Army Corps of Engineers, 1959); also, sections of track have been damaged or washed out in north San Clemente and along San Mateo Point, specifically during the floods of the 1880's and 1890's, 1916, 1927, 1938, 1939, and 1941.

5.238 Extremely wide beaches existed along this section of coast following the major and even minor floods, which, in effect, buffered wave erosion of the cliffs.

5.239 During the last major flood year, which occurred in March of 1938, a significant amount of sedimentary material moved onto local beaches. The U.S. Army Corps of Engineers (1959) indicated that

> "The quantity of sand placed on the the shore by the 1938 runoff [from San Juan Creek] is estimated at between 700,000 and 800,000 cubic yards. The resultant large deltas formed at the mouth of the creek during periods of runoff were rapidly distributed by wave action along the adjacent shores." The report (1959) continued:
>
> "The debris carried to the shore by San Juan Creek during times of flood runoff from these storms aids in maintaining the shoreline for some time subsequent to these storms."

San Onofre Creek to Santa Margarita River

5.240 Morphology. The San Onofre Creek to Santa Margarita River segment is approximately 15 miles long (Figure 50) and consists of 100-foot-high cliffs in the northern section to approximately 50-foot-high cliffs directly north of Santa Margarita River. The San Onofre Nuclear Power Plant, San Onofre State Park and Camp Pendleton are located on an uplifted colluvial terrace which is highly dissected by streams from runoff in the San Onofre Mountains to the east. The colluvial and underlying marine terrace deposits are essentially horizontal and are easily eroded along canyons and gullying of bluff faces.

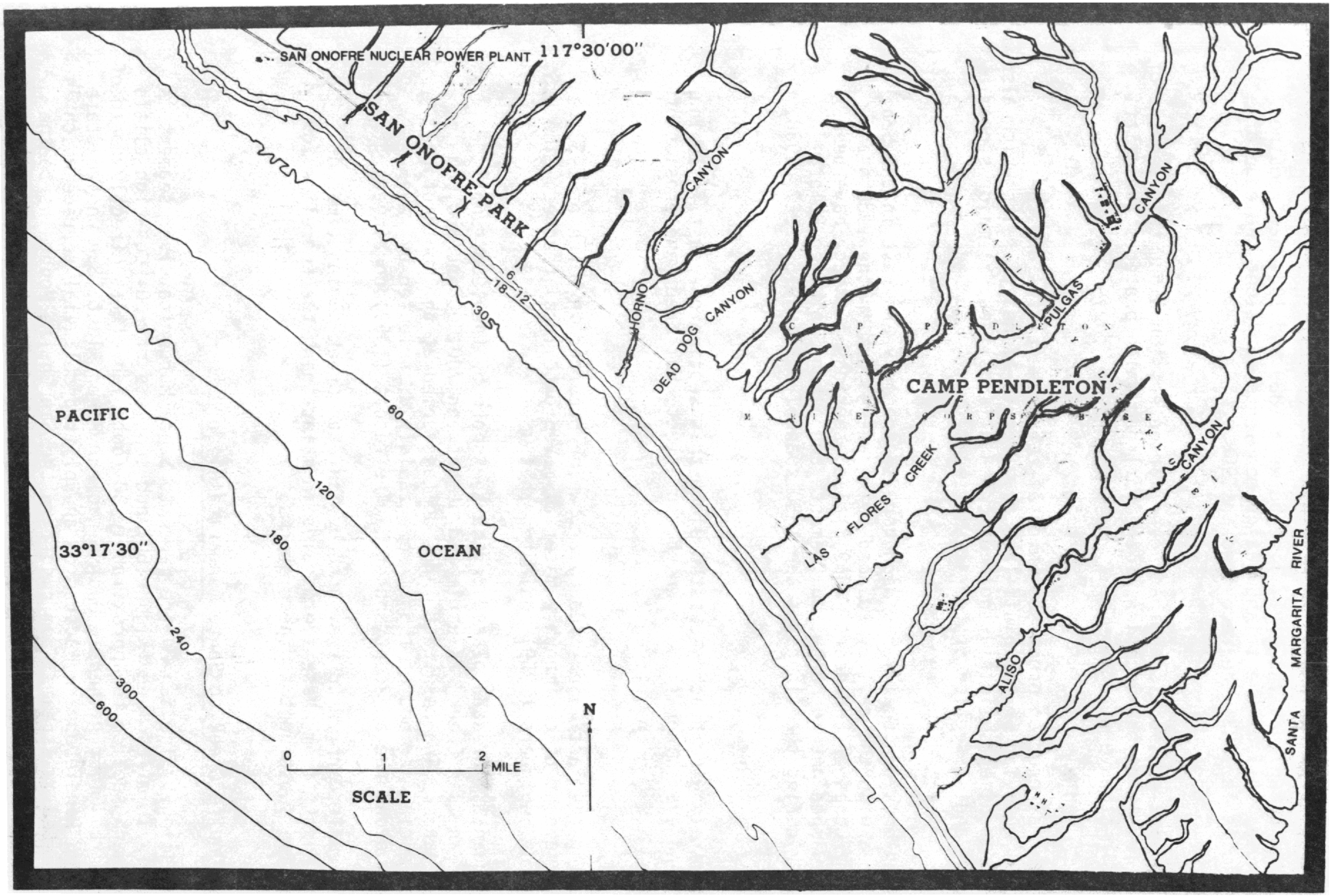


Figure 50. Location map of San Onofre State park and Camp Pendleton showing extensive drainage areas which flow across the coastal terrace. Note: Bathymetry is in feet (figure from Kuhn and Shepard, 1984).

5.241 Coastal Changes. Early studies of the area, conducted during a very stormy period in the 1880's by the U.S. Coast and Geodetic Survey (1889), indicated that the bluffs showed "new erosion during each winter storm as the characteristic feature of this coast". They also noted that the beaches from Los Angeles almost to San Diego were sufficiently wide and continuous to be traveled by horsedrawn vehicles.

5.242 Examination of the Coast and Geodetic Survey (1889) topographic field sheets in this area was made and then compared with the U.S. Geological Survey maps (1947-1948). No appreciable change is evident along the base of cliff or slope when the early maps (1889) is compared with the more U.S.G.S. map of 1948. The U.S. Army Corps of Engineers 1960) also indicated that an:

> "Examination of the Coast and Geodetic Survey field sheets in this area indicated that the bluff line between 1889 and 1934 had remained unchanged. All of the triangulation monuments set along the edge of the bluffs in 1933 were recovered in 1958."

5.243 However, this assertion of minimal erosion is not well justified. Actually there one major landslide and considerable canyon-cutting, bluff-face gullying and sloughing (Kuhn, Baker and Campen, (1980)., Kuhn and Shepard (1984), Kuhn and others (1987), and also significant surface erosion along the top of the coastal terrace.

5.244 Subaerial erosion of the coastal terrace and cliffs along San Onofre State Park and Camp Pendleton has contributed significant quantities of sediment directly to the beach locally during wet years. Erosion of the cliffs and coastal terrace along this coastal segment of the Oceanside Littoral Cell has contributed more sediment to the beach than all other coastal segments combined for the period between 1889 and 1947.

5.245 Between 1887 and 1947, significant coastal change has occurred along canyons and gullies, but no appreciable change is evident at the base of the cliff when plotted on the 1:24000 scale. Subaerial erosion processes are dominant over marine erosion, and marine erosion of the cliffs was negligible during the period studied. Erosion of the coastal terrace has contributed a significant source of sediment directly to the beach, which acts as a buffer to marine erosion.

5.246 Subaerial erosion processes which occur along this coastal segment are: 1) rainfall induced landslides and surface erosion of the top of the coastal terrace, 2) lateral and headward erosion along canyons cut into the coastal terrace as a result of man's alteration of existing drainage patterns by diverting surface runoff which fell as rain in the San Onofre Mountains directly east of the coastal terrace and focused the runoff into storm drain culverts located under the freeway, which subsequently incised the coastal terrace; and 3) gullying of the coastal terrace and cliff face by rain wash.

5.247 Approximately 80 percent of the cliffs between the Nuclear Power Plant and Dead Dog Canyon to the south consists of landslides (Figure 21). Many of the landslides appeared to be of recent origin when viewed on the U.S. Coast and Geodetic Survey maps (1889). The landslides appear to be directly related to intense saturation of the strata comprising the coastal cliffs and heavy surf associated with large storm swell. In this century, these conditions occurred only during extremely wet years: namely, 1941 and 1978 (Kuhn, Baker and Campen, 1980). The landslide which occurred in 1941 measured 1700 feet in length and 350 feet in width, and was along a seaward-dipping plane (Figure 51).

5.248 Since 1885, normal erosion along all drainage avenues has been drastically altered by man. Railroad trestles were built across canyons in 1885, but apparently they did not alter the drainage pattern. The construction of Highway 101, beginning in 1912 through 1918, first altered the natural drainage patterns with the installation of culverts under the highway to channel surface runoff. In the wet years that followed, gully erosion was accelerated where the culverts concentrated water flow.

5.249 Dead Dog Canyon, south of Horno Canyon in Camp Pendleton, was seen as just a notch on the cliff top in 1889 (Figure 52). Between 1889 and 1932 it eroded landward very little (Figure 53), and between 1932 and 1977 it enlarged 560 feet headward. In 1978 the canyon eroded another 100 feet (Figure 54b), and another 100 feet eroded in February 1980 (Figure 54c).

5.250 Gullies cut into the coastal terrace and cliff face contribute significant amounts of coarse-grained sediment by increasing the surface area of cliff material exposed to erosion (Figure 55).

5.251 In 1889, at the present location of the San Onofre Nuclear Power Plant, barranca and gullying was apparent (Figure 56). Photographs taken in 1932 (Figure 57), 1941 (Figure 58), 1953 (Figure 59), 1964 (Figure 60), and 1972 (Figures 61, 62) clearly illustrate marked headward erosion across the coastal terrace.

5.252 Between 1887 and 1947, the beaches in this area varied in width from 40 to 400 feet wide. Extremely wide beaches existed along this section of coast following the major storm flood years, which deposited large amounts of sedimentary material along the coast from rivers and erosion of the coastal terrace. The most important storm/flood years occurred during the 1880's, 1890's, 1916, 1927, 1938, 1939 and 1941.

Santa Margarita River to San Marcos Creek (Batiquitos Lagoon)

5.253 Morphology. The terraces of the Camp Pendleton area terminate with the entrance of the San Luis Rey and Santa Margarita Rivers which extend into the coast just north of Oceanside. The City of Oceanside is built on the low terrace margin of Pleistocene non-marine origin, which extends southward into Carlsbad, and is about 30 feet above sea level (Figure 63).

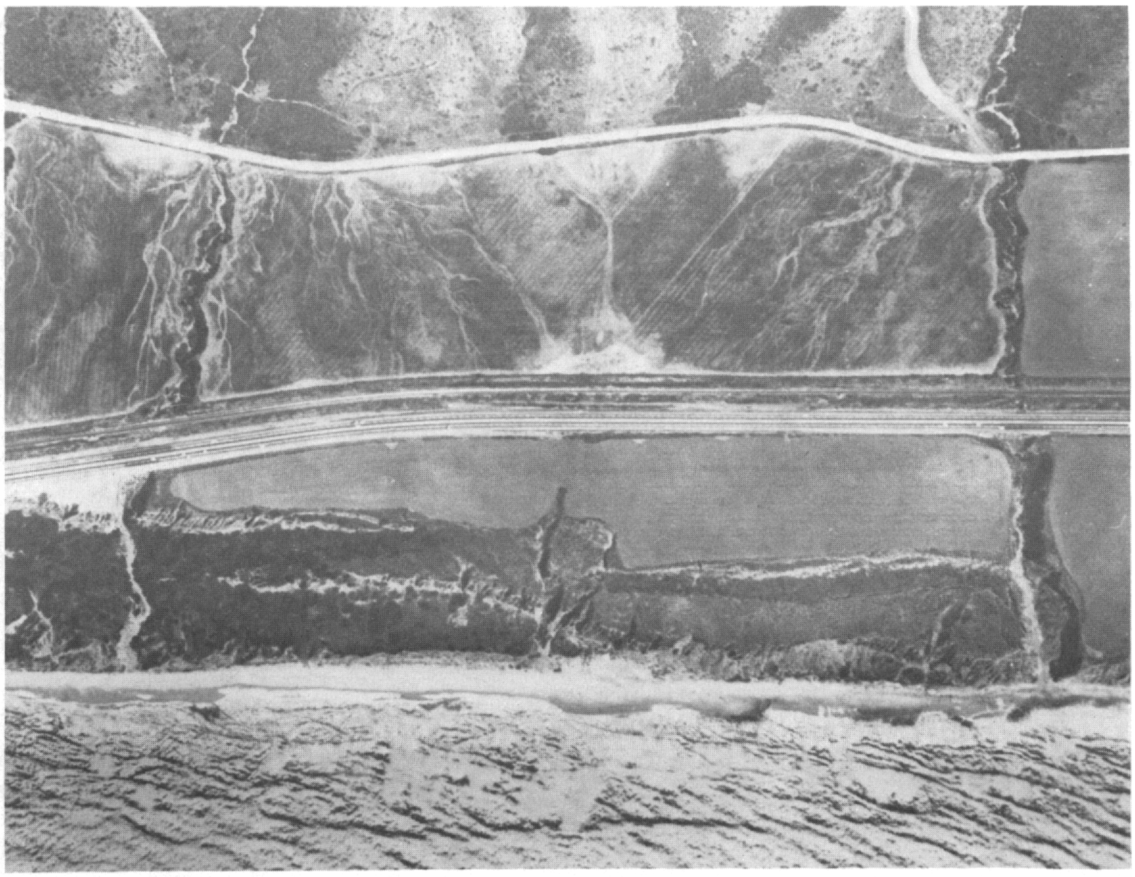


Figure 51. 1953 vertical aerial view looking northeast across the landslide which occurred in June, 1941. The landslide is 1700 feet long and 350 feet wide, and was along a seaward-dipping plane (photograph by U.S. Department of Agriculture).

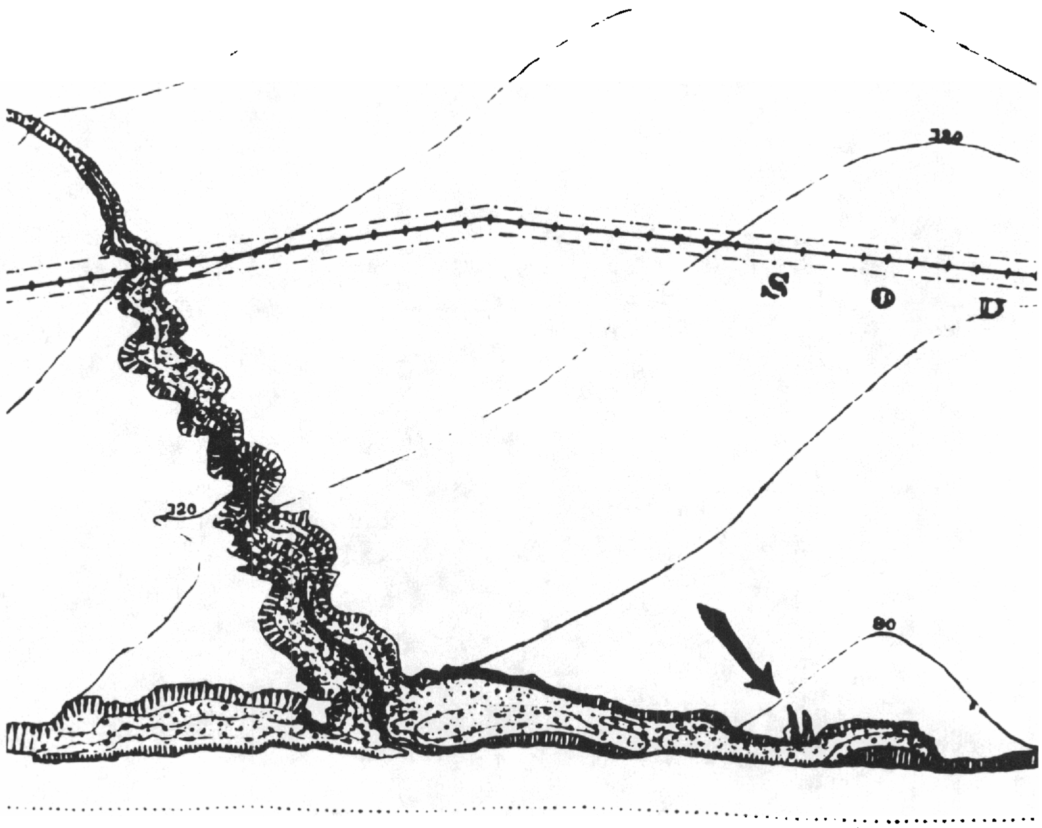


Figure 52. Map view of Horno Canyon (large canyon to left in figure) and beginning stages of Dead Dog Canyon (see small arrow) in 1889 (from U.S. Coast and Geodetic Survey Map, Topographic map No. T-2015, 89).

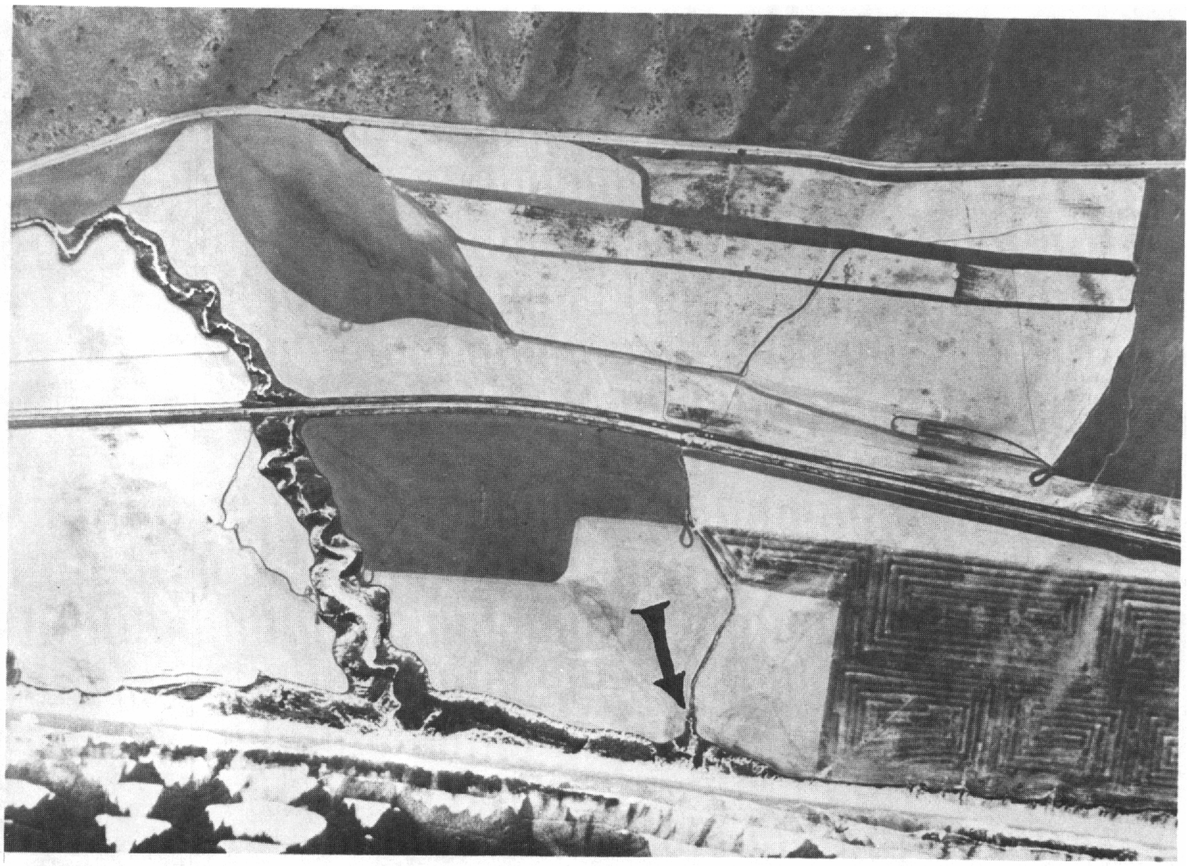
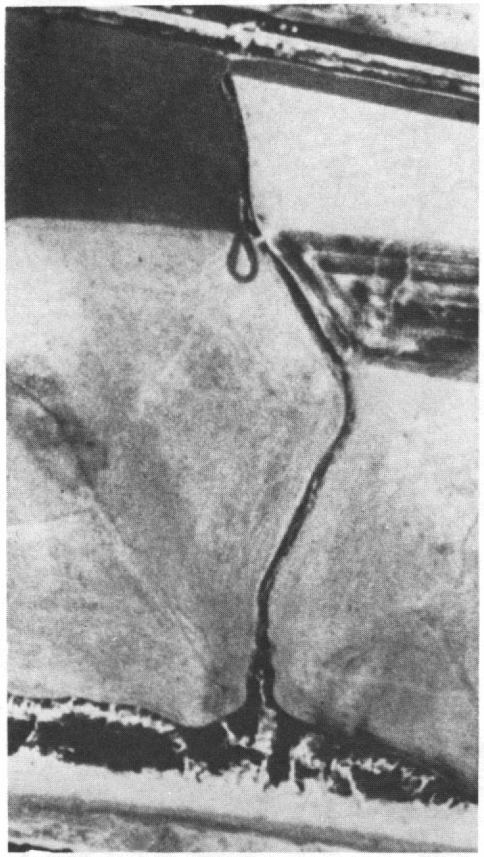


Figure 53. Aerial view in 1932 of same canyons as seen on Figure 52 (1889). Note: Small canyon to right (Dead Dog Canyon see arrow) had eroded landward very little during this period (photograph from Whittier College Collection).

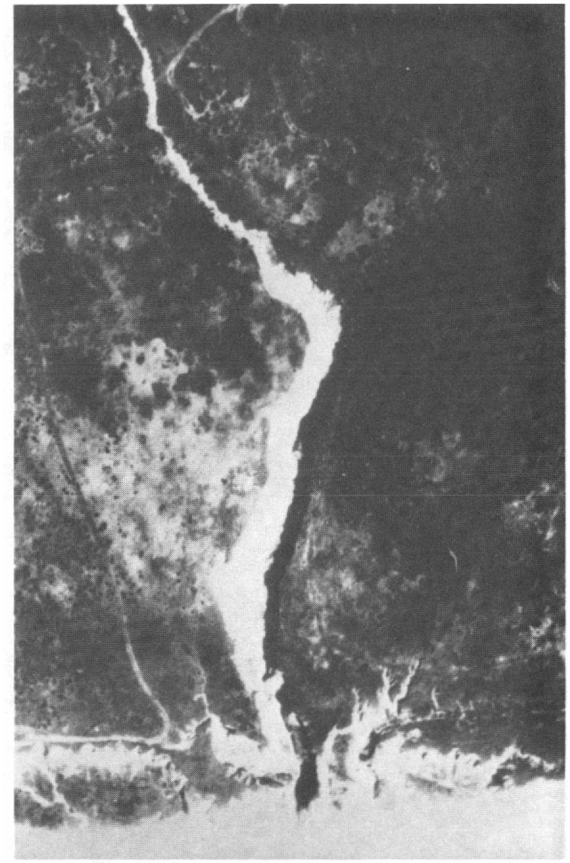


A

Figure 54a. Vertical aerial photograph of small canyon (Dead Dog) forming on the edge of the coastal terrace at Camp Pendleton in 1932. Same Canyon as seen on figures 52, 53 (photograph from Whittier College Collection).

B

Figure 54b. 1979 vertical aerial photograph of same canyons as seen on figures 52, 53, 54a (photograph by Scripps Institution of Oceanography photographic laboratory).



C

Figure 54c. 1985 vertical aerial photograph of same canyons as seen on figures 52, 53, 54a, 54b (photograph by Scripps Institution of Oceanography photographic laboratory).

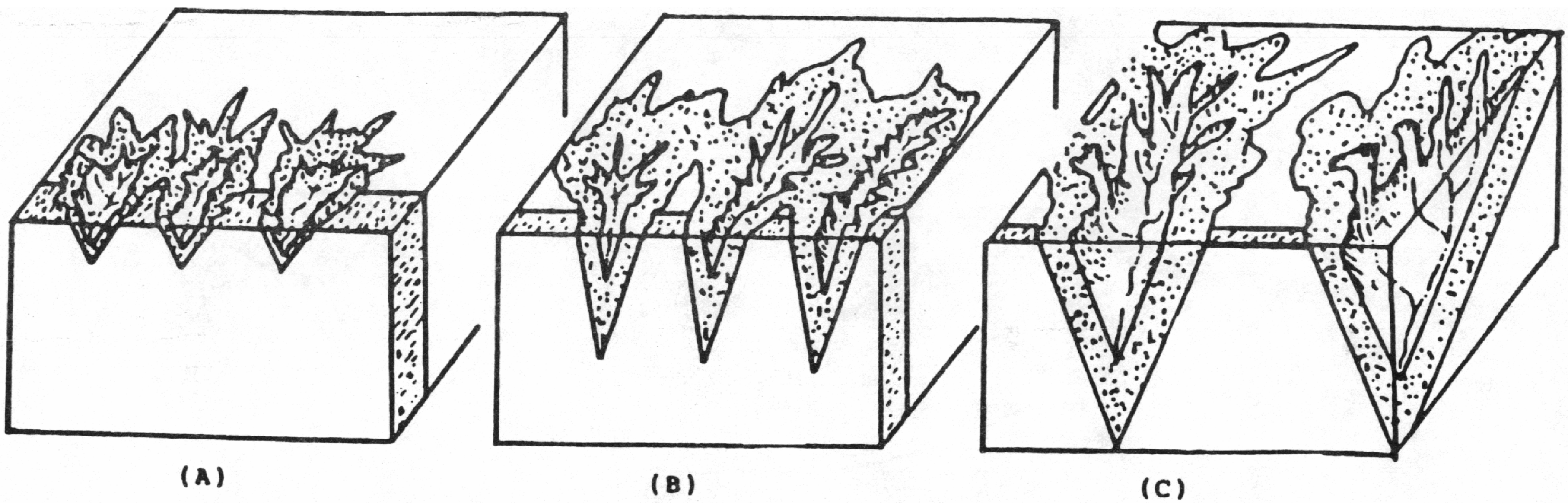


Figure 55. Diagram illustrating cliff and gully erosion from Osborne and Pipkin (1983) and Corps of Engineers Report #CCSTWS 84-4.

Notes: 1. Schematic diagram showing relative volume of sediment produced by cliff-face retreat (short dashed lines) and the volume of sediment produced by headward erosion (stippled area) of major gullies. (A) Indicates cliff-face erosion greater than gullying. (B) Cliff-face erosion about equal to gullying. (C) Gully erosion greater than cliff-face erosion.

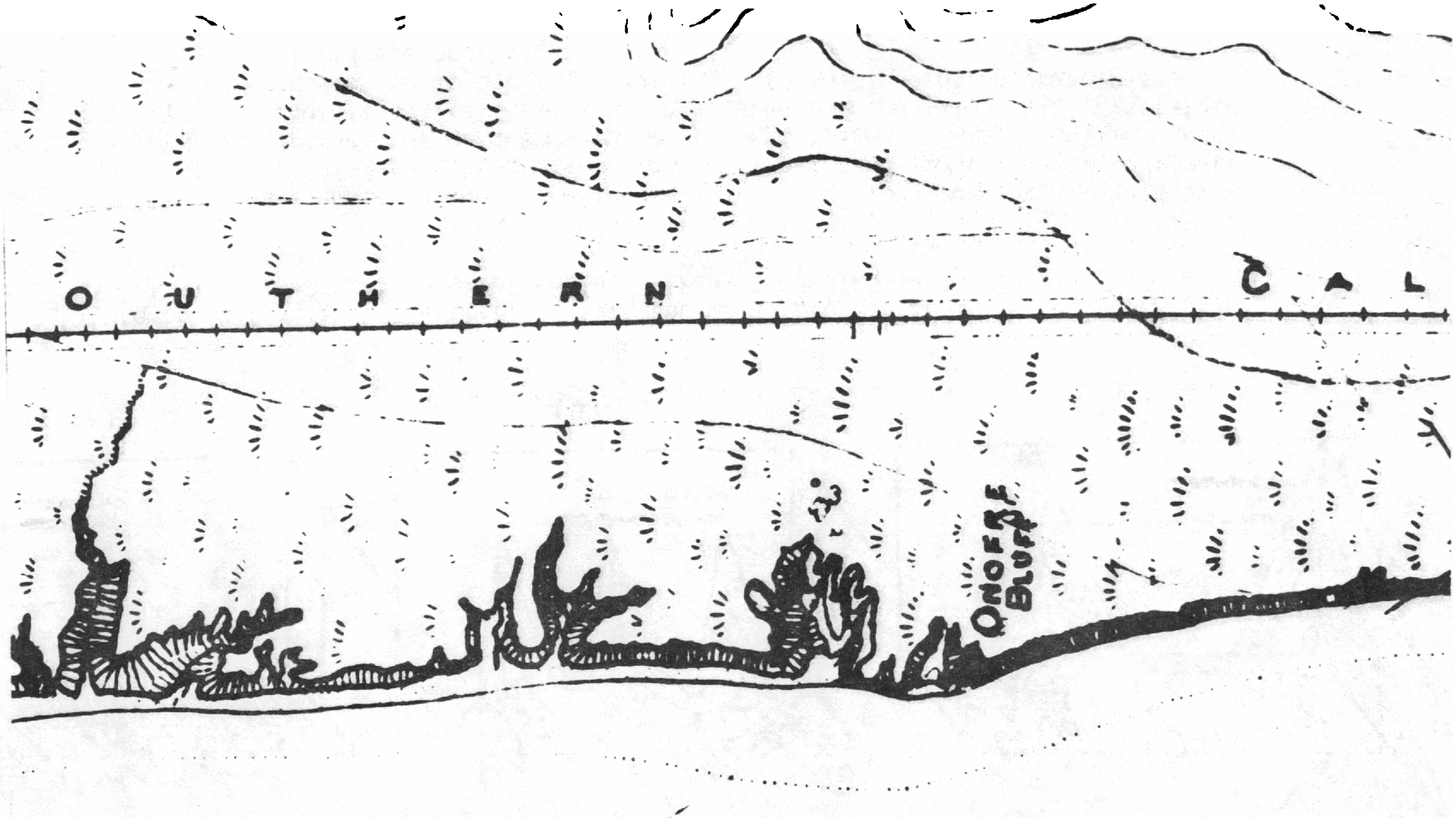


Figure 56. U.S. Coast and Geodetic Survey Map of San Onofre area in 1889. Note: Barranca gully developed in coastal terrace (from U.S. Coast and Geodetic Survey Topographic Map #T-2016, 1889).

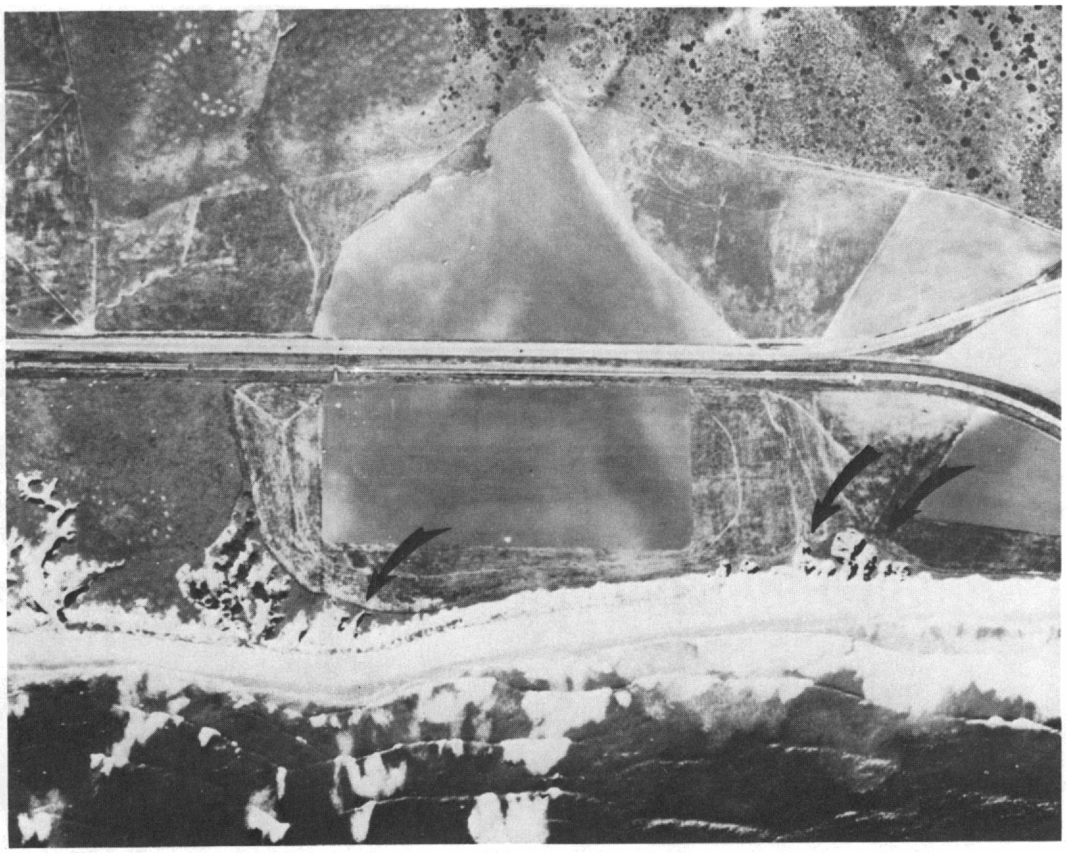


Figure 57. Vertical aerial view of coastal terrace in 1932 at the present site of the San Onofre Nuclear Power Plant. Arrows point to barranca-gully development along edge of terrace (photograph from Whittier College Collection).

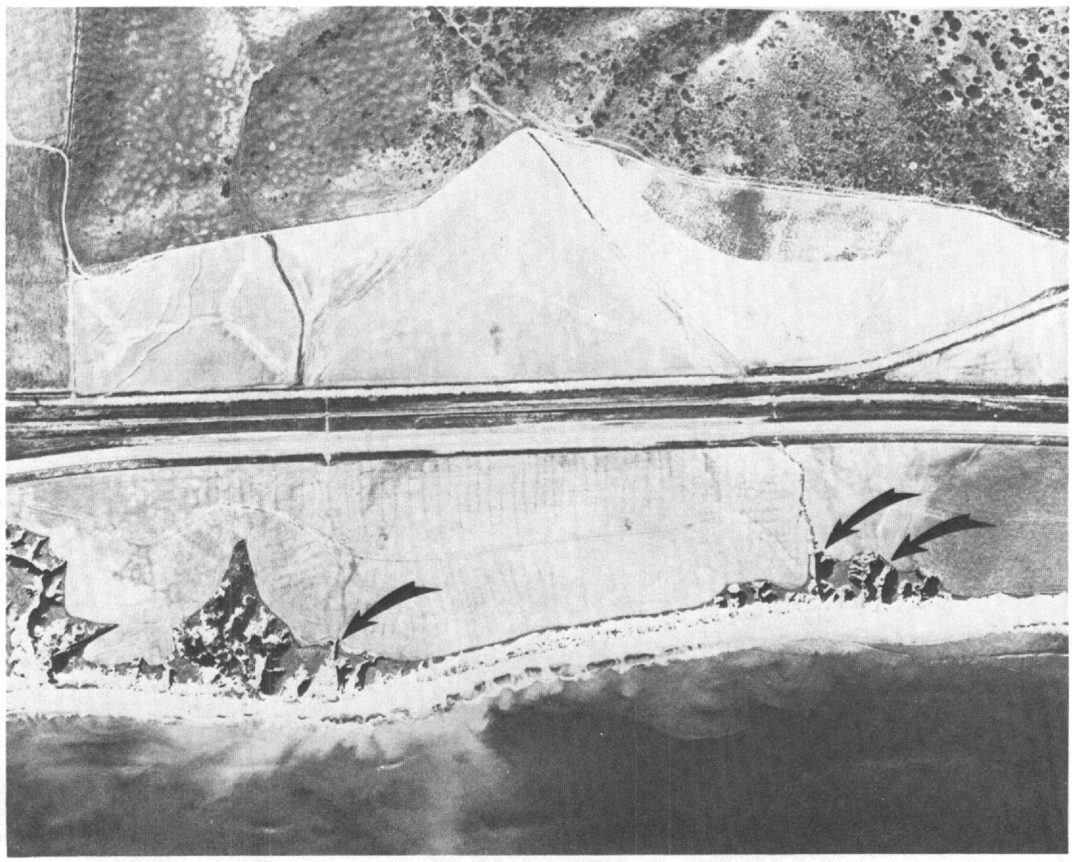


Figure 58. Vertical aerial view of the coastal terrace in 1941 at the present site of the San Onofre Nuclear Power Plant. Arrows point to barranca-gully development along and into coastal terrace (photograph by U.S. Geological Survey).

Figure 59. Vertical aerial view of the coastal terrace in 1953 at the present site of the San Onofre Nuclear Power Plant. Arrows point to Barranca-gully development along and into coastal terrace (photograph by U.S. Department of Agriculture).

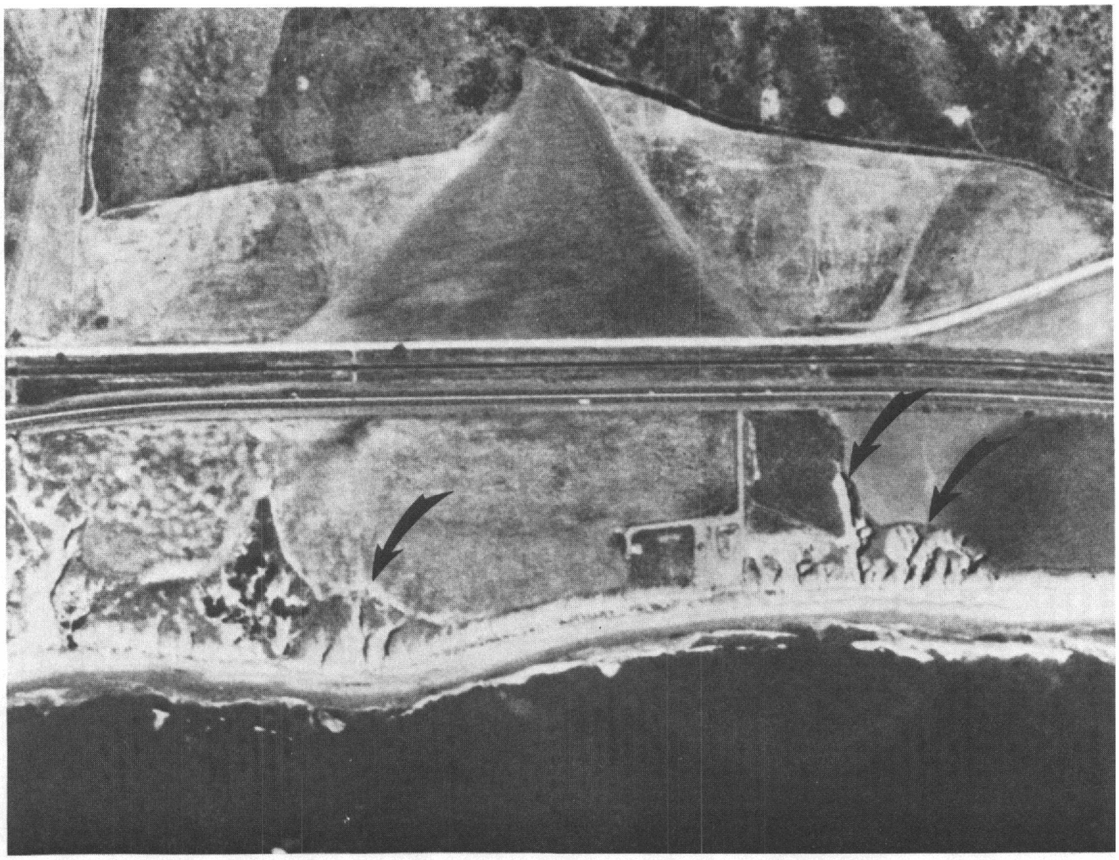


Figure 60. Vertical aerial view of the coastal terrace in 1964 at present site of San Onofre Nuclear Power Plant. Same site as seen on Figures 56 (1889), 57 (1932), 58 (1941) and 59 (1953) (photograph from California Coastal Commission files).

Figure 61. 1972 vertical aerial view of same site as seen on Figures 56 (1889), 57 (1932), 58 (1941), 59 (1953) and 60 (1964). Note: Gullying of coastal terrace has greatly accelerated since 1889 (photograph from California Coastal Commission Files).

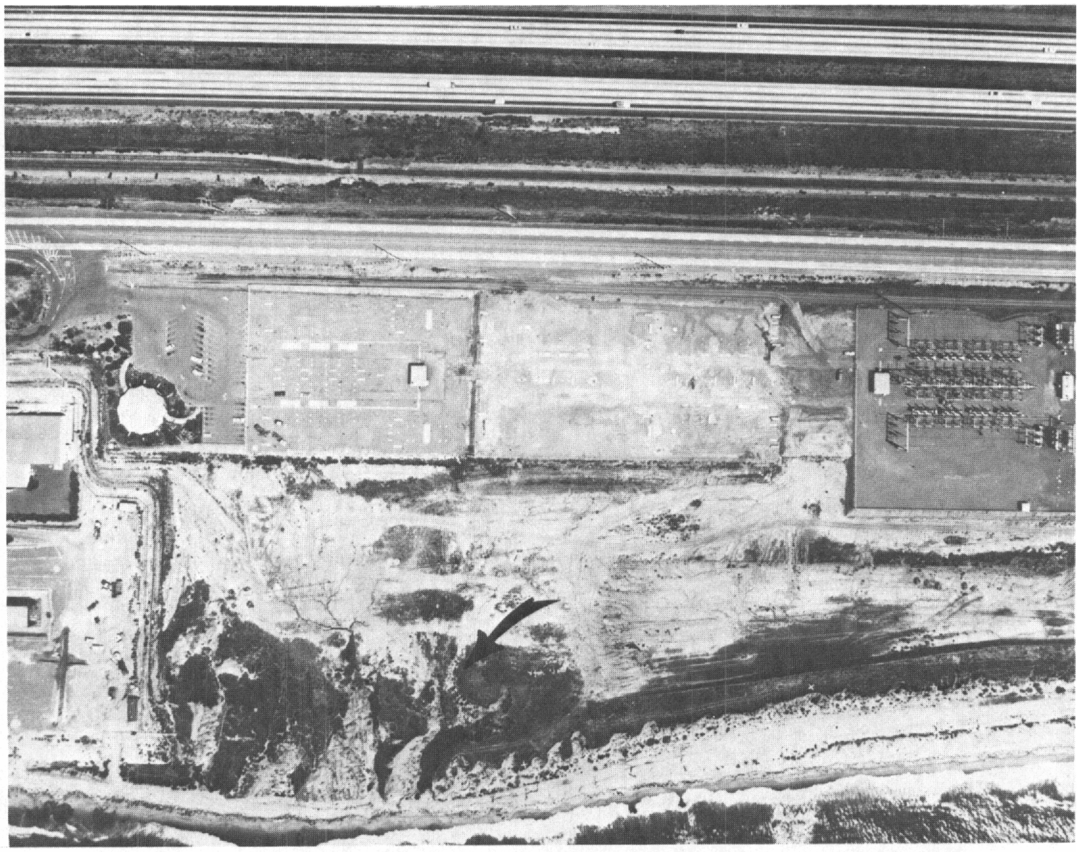


Figure 62. 1972 vertical aerial view of same site as seen on Figures 56 (1889), 57 (1932), 58 (1941), 59 (1953), 60 (1964), and 61 (1972) (photograph from California Coastal Commission files).

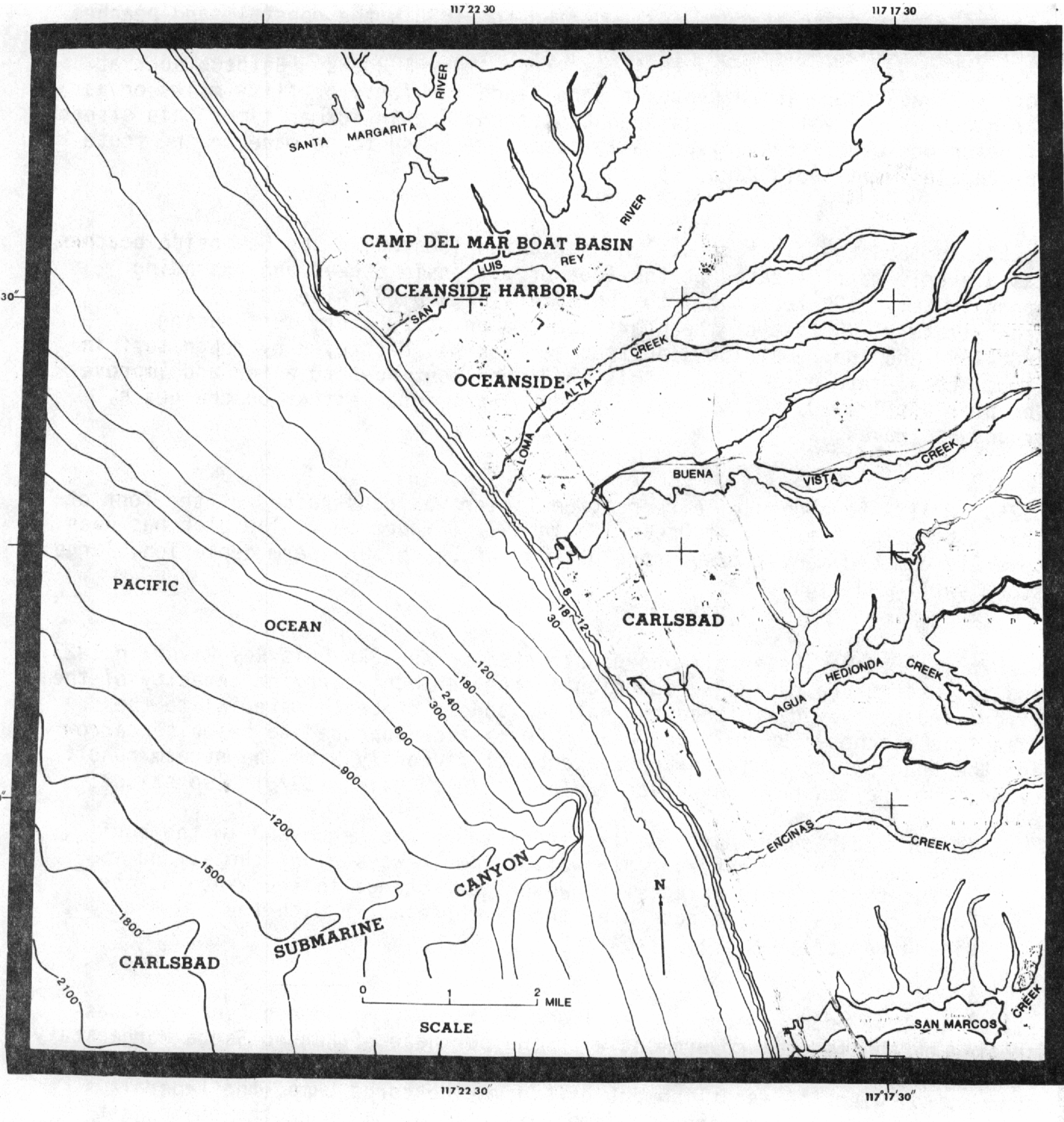


Figure 63. Location map from Santa Margarita River mouth through Oceanside, and Carlsbad to San Marcos Creek at Batiquitos Lagoon. Note: Bathymetry is in feet (figure from Kuhn and Shepard, 1984).

5.254 Prior to 1900 the beach served as the most heavily traveled "highway" along the California coast. After the turn of the century the beach was even used as a race track (Figure 64). During the 1880's the coastal sand beaches varied in width from 100 to 300 feet (Figures 65, 66). The Coast and Geodetic Survey (1889) noted that "... from 'Mussel Rocks' [Bathtub Rock at Torrey Pines] there is an unbroken sand beach for forty or fifty miles or as far north as the valley of San Juan Capistrano and in former times this stretch of beach was used whenever specially fast time [was] to be made on the route Los Angeles, via Capistrano, to San Diego."

5.255 In 1888 the first coastal construction located on the Oceanside beaches was a supply wharf located at the foot of Wisconsin Street and extending approximately 1500 feet out into the water (Figure 67, site "D"). Approximately 390 feet of the wharf was broken up by storm surf during 1888-1889 and the remaining 1140-foot section was destroyed by rough surf in 1890. Local interests rebuilt this wharf and continued to alter and improve the pier until 1920, but without apparent detrimental effect on the beach processes (Hales, 1978).

5.256 A 1132-foot open pile recreational pier was constructed at the foot of Third Street by the City of Oceanside in 1927 (Figure 68). The pier has been severely damaged many times during periods of beach sand berm depletion, large storm swell and high tides.

5.257 The Henshaw Reservoir was constructed on the San Luis Rey River in 1923, and this structure caused a reduction in the sediment-carrying capacity of the river, and thereby diminished the natural supply of beach material to the Oceanside beaches. By 1925 the usable beach area appeared to be quite narrow and the beach width could be correlated satisfactorily with the stream runoff rates from the San Luis Rey River (Hales, 1978). Hales (1978) also stated:

> "Minor additional improvements were made on the beach and in the surf zone, such as concrete curtain wall and walk-ways along the strand with definite groin effects. However, any change in the width of the beach could always be accounted for by correlation with the discharges of the local streams."

5.258 In 1942 under emergency wartime conditions Camp Joseph Pendleton was created by the federal government with the purchase of Rancho Santa Margarita y Las Flores, immediately adjacent to the northern limits of Oceanside. In conjunction with the establishment of the marine corps camp, the federal government built a jetty and the Camp Del Mar boat basin on the beach just north of the city limits in order to provide Camp Pendleton with a harbor facility. The boat basin site was subsequently dredged and the dredged material was placed around the boat basin perimeter to elevate the grade for building areas. The dredged spoil material consisted not only of sand, silt, clay and mud but also extensive flood-derived cobble lenses. The original harbor construction consisted of two converging jetties extending seaward to about 20-ft depth; the upcoast rubble mount jetty length was approximately 1296

Figure 64. View looking north along the beach at Oceanside in 1913. Automobiles were racing five abreast on the extremely wide beach (photograph from Title and Trust Insurance, Co. Inc. Collection).

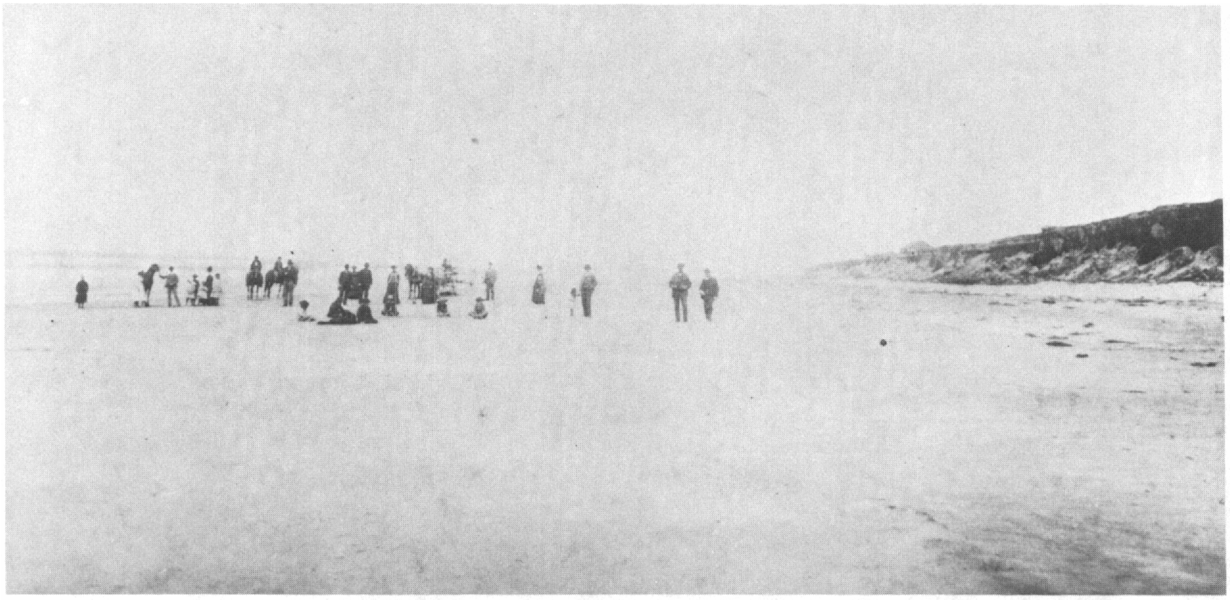


Figure 65. Winter view along the beach at the future site of City of Oceanside in 1883. Note the extremely wide beach and landslides along the cliff face. Caption is "Everyone in north San Diego County" (photograph courtesy of Union Title and Trust Co.).

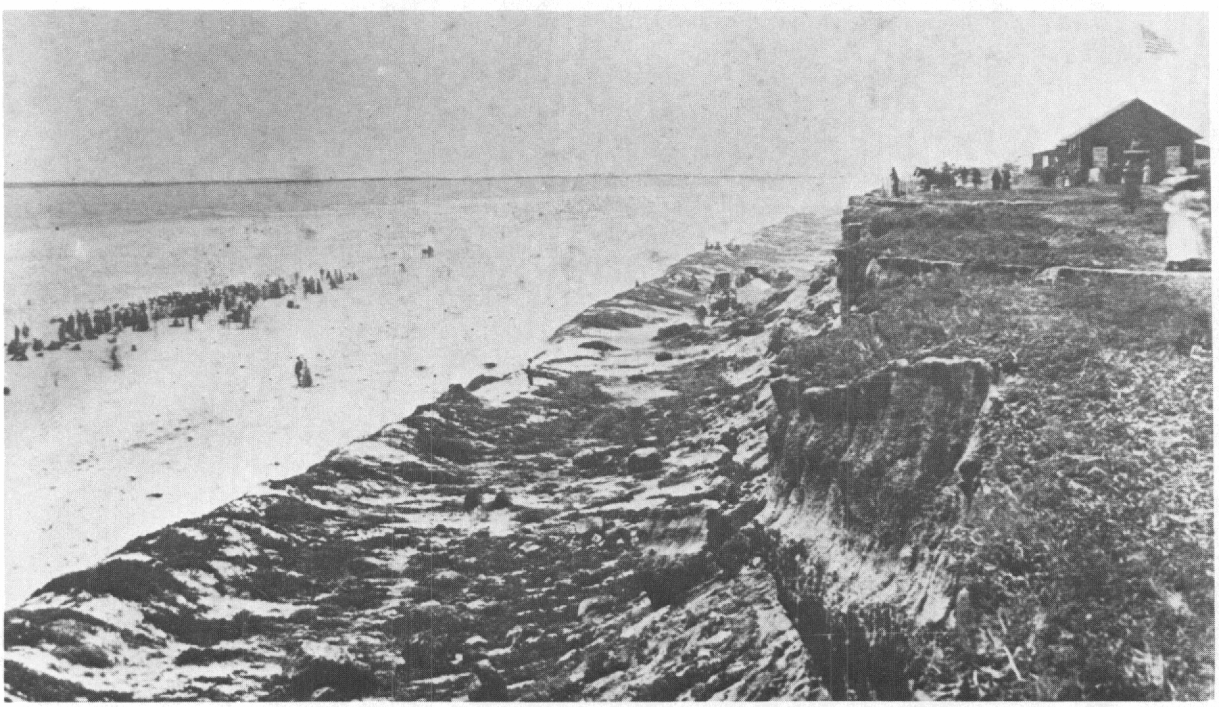


Figure 66. Summer 1885 photograph looking north along bluffs at Oceanside with wide beach below. Note: Extensive landslide material fronting the cliffs, showing predominance of subaerial erosion and lack of wave erosion (photograph from F. P. Shepard Collection).

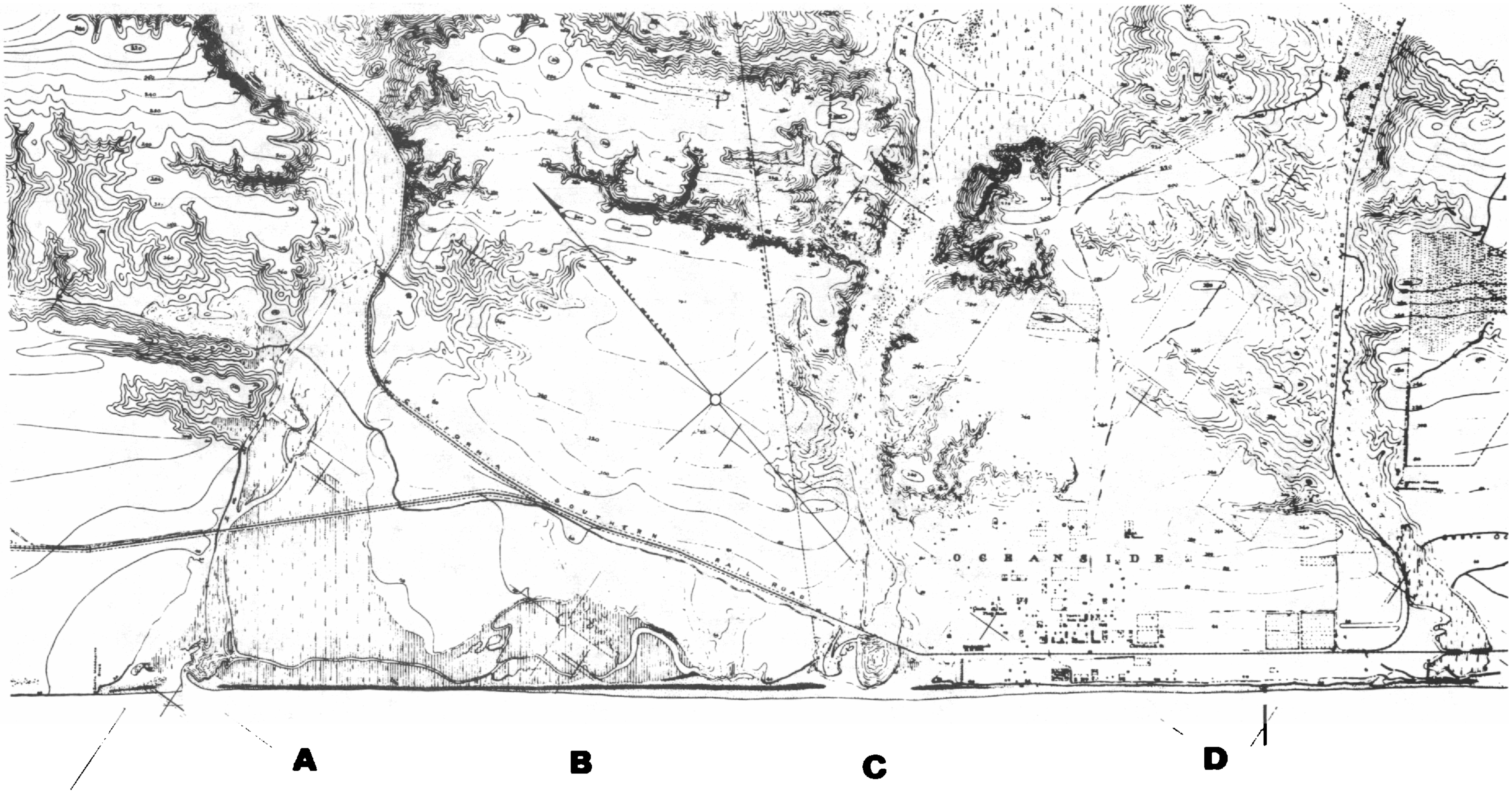


Figure 67. 1889 map view of Oceanside area (from U.S. Coast and Geodetic Survey, 1889, Topographic Map No. #T-1900).

A. Santa Margarita River
B. Estuary Complex
C. San Luis Rey River
D. Wisconsin Steet

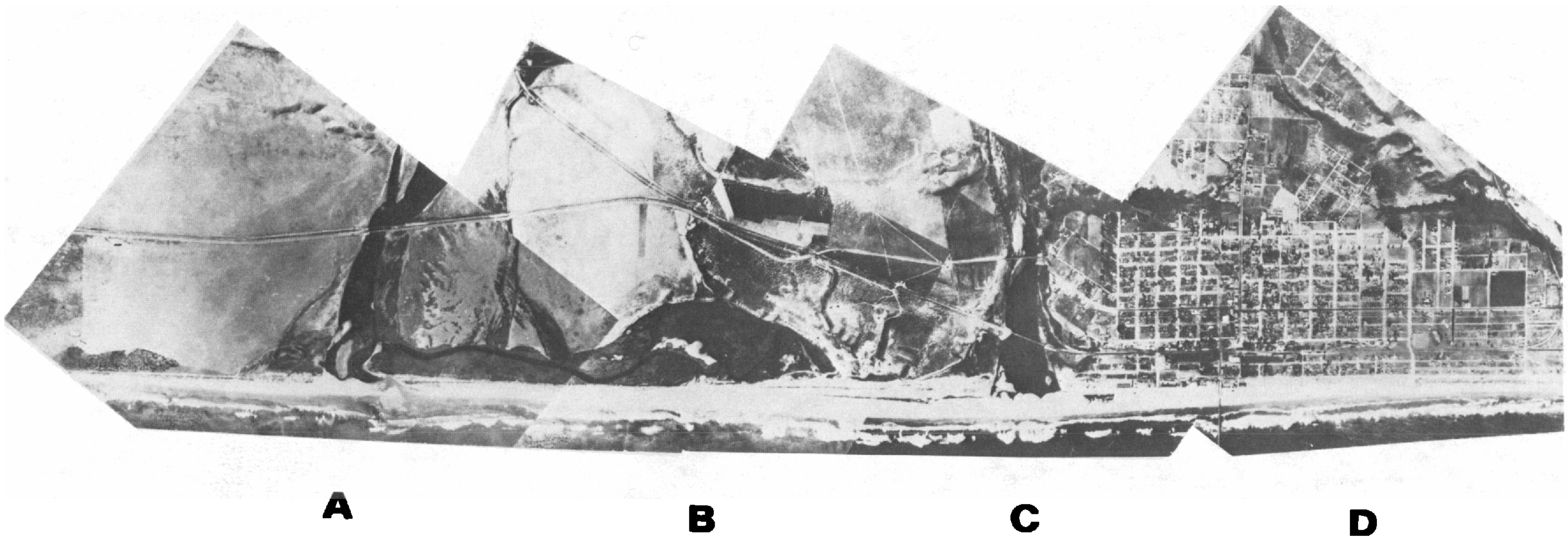


Figure 68. Vertical aerial photograph of Oceanside area in 1928. A., B., C., and D. locations are the same as seen on Figure 67 (1889) (photographs from County of San Diego Surveyors Office).

feet long and downcoast jetty approximately 1300 feet long (Hales, 1978). The erosion of the beach in the vicinity of Oceanside was visible during harbor construction. Sediment was impounded on the north and shoaling occurred across the harbor channel entrance (Shaw, 1980).

5.259 In the U.S. Army Corps of Engineers report on Oceanside, Hales (1978) indicated:

> "By 1944-45, the entrance channel had shoaled from a constructed depth of 20 ft to only 14 ft and had decreased in width from 190 ft to 50 ft. Littoral material apparently from an upcoast source had accreted on the north side of the north jetty. The entrance channel was dredged with approximately 219,000 cu yds of material being removed and placed as land reclamation fill. Within 8 months of the dredging an equivalent amount of material had again been deposited in the harbor.
>
> During construction of the harbor in 1942 and 1943, erosion of the beach in the vicinity of Oceanside was noticeable. Shortly after completion of the harbor, the littoral drift from upcoast apparently passed sand around the upcoast jetty and shoaled across the entrance channel to the harbor. When the entrance channel was shoaled across, erosion of the downcoast beaches was no longer apparent. After maintenance dredging was undertaken in 1945, erosion again occurred. However, the entrance channel again shoaled and the erosion was once again halted.
>
> From these observations it became apparent that if the entrance to Del Mar Boat Basin was maintained to project depths and widths, it would become necessary to by-pass sand past the entrance periodically, both to maintain the harbor without constant maintenance dredging and to prevent erosion damages to the downcoast beaches".

5.260 Between 1948 and 1977 the Oceanside area showed a history of shoreline problems down coast of the harbor. (For more detailed information see Hales (1978), and Kuhn and others (1987).

5.261 Coastal Changes. Erosion of the cliffs along north Oceanside have, for the study period, not contributed any appreciable sediment to local beaches. These cliffs are separated from the beach by a riprap wall, the coastal road, and buildings constructed on the former beach. The cliffs at Carlsbad also have not contributed any appreciable sediment to local beaches as many seawalls and buildings separate the cliffs from the beach.

5.262 The U.S. Coast and Geodetic Survey mapped the topography and bathymetry of this coast beginning in 1887 and finished in 1890. The maps were filed in the U.S.C.G.S. Archives in April 1891. The mapping took longer than was the norm as a results of flooding and heavy rains (U.S.C.G.S. Report to the Superintendant of the Survey (1890).

5.263 Examination of these early U.S. Coast and Geodetic Surveys topography field sheets were made and were then compared with the U.S. Geological Surveys of 1947 and 1948. No appreciable change along the base of cliff or slope is evident.

5.264 Subaerial erosion processes have, for the most part, been dominant over marine erosion for the period between 1887 and 1947. The cliffs above the beaches were retreating during the 1880's as the result of subaerial erosion during this wet period (Kuhn and Shepard, 1984) (Figure 65, 66).

5.265 Subaerial erosion processes which have accelerated erosion of these cliffs are as follows: 1) spring sapping by ground water along the cliff face which may initiate landslides; 2) surface runoff along street ends which flows down the cliff face, 3) erosion of the cliff face as a result of heavy rainfall; 4) collapse of storm drains designed to carry surface water runoff away from cliff faces; 5) overwatering of non-native vegetation along the cliffs, and 6) at many sites pedestrian foot traffic along the cliffs.

5.266 Marine erosion of beaches in Oceanside and Carlsbad, prior to construction of the Del Mar Boat turning basin at Oceanside (Figure 69), was locally severe at specific sites most recently during the storms of 1939, 1940 and 1941 (Figure 70).

5.267 The last storm/flood year to contribute a large amount of material to most of the southern California beaches was 1938 (Troxell and others, 1942). Following the 1938 flood year the beaches were considerably widened and the tourist trade flourished (Figure 71).

5.268 Storms waves from a tropical storm in September 1939 removed much of the beach. Wave heights were reported to have been well over 25 feet near the present harbor at Oceanside (Marine Advisors, 1960).

5.269 Between December 23, 1940 and January 7, 1941, a series of storm fronts which originated in the Aleutian Islands moved into southern California doing considerable damage to beach front and bluff top property (Kuhn and Shepard, 1979). Houses in South Oceanside and Carlsbad were destroyed (Figures 72, 73) and the beach berm was severely eroded. During the storms a thirty foot swell running along the coast coincided with gale force winds and occurred on the perigean spring tide. Near Wisconsin Street in Oceanside "Serano Court" was damaged. The San Diego Union, December 27, 1940, stated:

> "High tides and a pounding sea continued to damage the Oceanside shoreline. Combers broke over the end of the pier at high tide today. A crew of men worked all day yesterday and today to save El Sereno Court from being swept out to sea. Sandbags have been piled high against the buildings. The Arthur Neff home, which has been protected by a retaining wall has received a severe buffeting from the sea. Foundations of the Guy Sensaba home are menaced. Precautions were taken today to hold back the sea."

Figure 69. Oblique aerial view looking south across the Oceanside Harbor in 1974 (seen on Figures 67 and 68-"B", photograph by G. Kuhn).

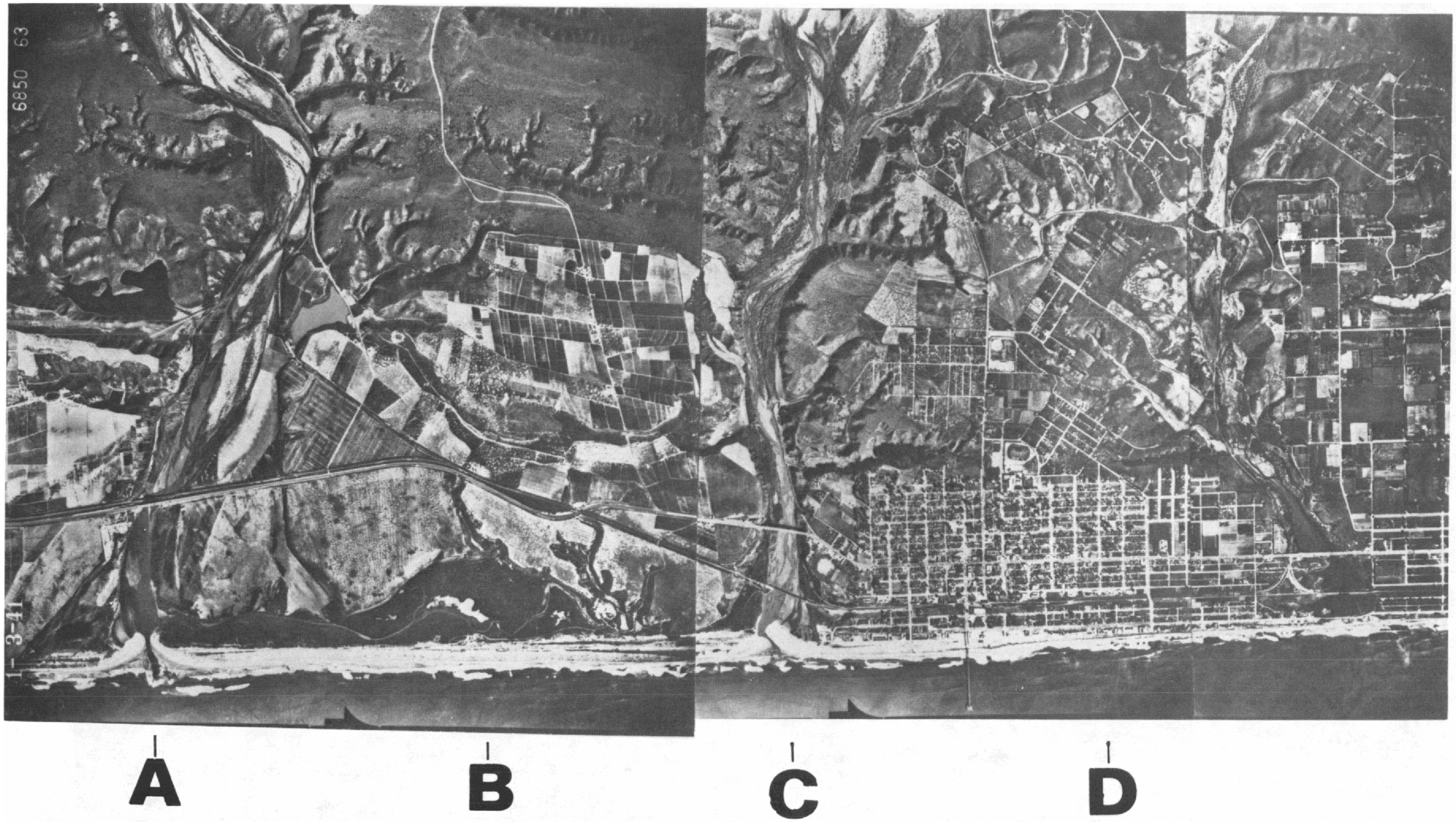


Figure 70. Vertical aerial view of Oceanside area in January 1941. Sites A., B., C., and D. are same as seen on Figure 67 (1889) and Figure 68 (1928) (photographs from the U.S. Geological Survey Archives).

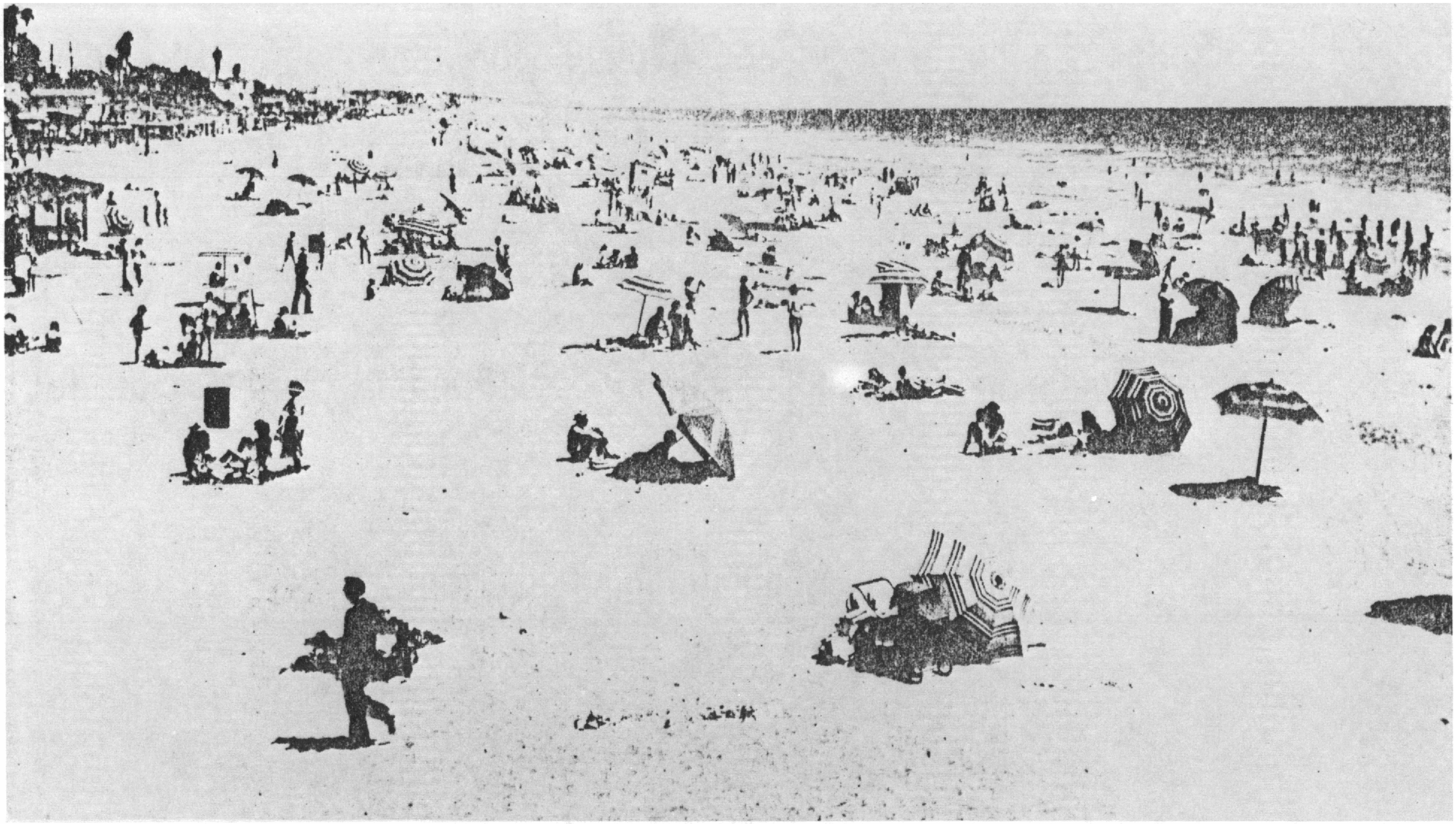


Figure 71. View looking south along the extremely wide beach just south of Oceanside pier in July 1939. Beach was markedly widened following the flood of March 1938 (photograph from U.S. Army Corps of Engineers, 1960).

Figure 72. View of storm damage along Cabana San Malo, South Oceanside (photograph by D. L. Inman).

Figure 73. View looking north along the cliffs at Carlsbad in January 1941. Beach cottages were damaged or destroyed during this storm period (photograph by D. L. Inman).

Batiquitos Lagoon to San Dieguito River

5.270 Morphology. The communities of Leucadia, Encinitas and Solana Beach to the south are located on beach and dune ridges of Pleistocene marine and non-marine origin about 80 to 120 feet above sea level (Figure 74). The cliffs on the seaward side consist of ancient lagoonal-barrier sand bars and open coast sediments.

5.271 Coastal Changes. Erosion of the cliffs along Leucadia, Encinitas, Cardiff and Solana Beach has not contributed appreciable sediment to the beach during the period studied.

5.272 The U.S. Coast and Geodetic Survey mapped the topography and bathymetry of this coast beginning in 1887 and finished in 1890. The maps were filed in the U.S.C.G.S. Archives in April 1891. The mapping took longer than was the norm as a results of severe sea storms which produced heavy rains and flooding (U.S.C.G.S. Report of the Superintendant of the Survey (1890).

5.273 Examination of these early U.S. Coast and Geodetic Survey topographic field sheets (filed in 1891) were made and the surveys were compared with the U.S. Geological Survey of 1948. Little change is evident along the base of cliff of slope toe using the 1:24000 scale maps of the U.S. Geological Survey.

5.274 The U.S. Army Corps of Engineers (1960) also indicated that:

> "The field sheets of the 1887 and 1934 surveys were examined and no difference could be found in the location of the bluff lines as shown on the sheets, and it is believed that no serious bluff erosion occurred along this section of the coast between 1887 and 1934. Several longtime residents of Encinitas and Leucadia were interviewed and all stated that to their knowledge there have been no large slides along the bluffs due to erosion or undercutting by wave section."

5.275 However, it appears that significant coastal change was recorded at Encinitas between 1881 and 1890 (Kuhn and Shepard, 1981, 1984). As mentioned previously in paragraphs 5.60 through 5.92, numerous maps were filed with the State of California and County of San Diego before the U.S. Coast and Geodetic Survey began mapping the coastline at this location in 1887.

5.276 The California Southern Railroad mapped their railroad right of way in 1880 (Figure 9), 1881 (Figure 10), and 1883 (Figure 11). The town of Encinitas was surveyed in March of 1883 (Figure 12). All these maps showed the same coastal configuration. Following the great storms of 1884 through the tropical storm of October 1889, the coastline eroded landward. When the U.S. Coast and Geodetic Survey began surveying this section in 1887, change

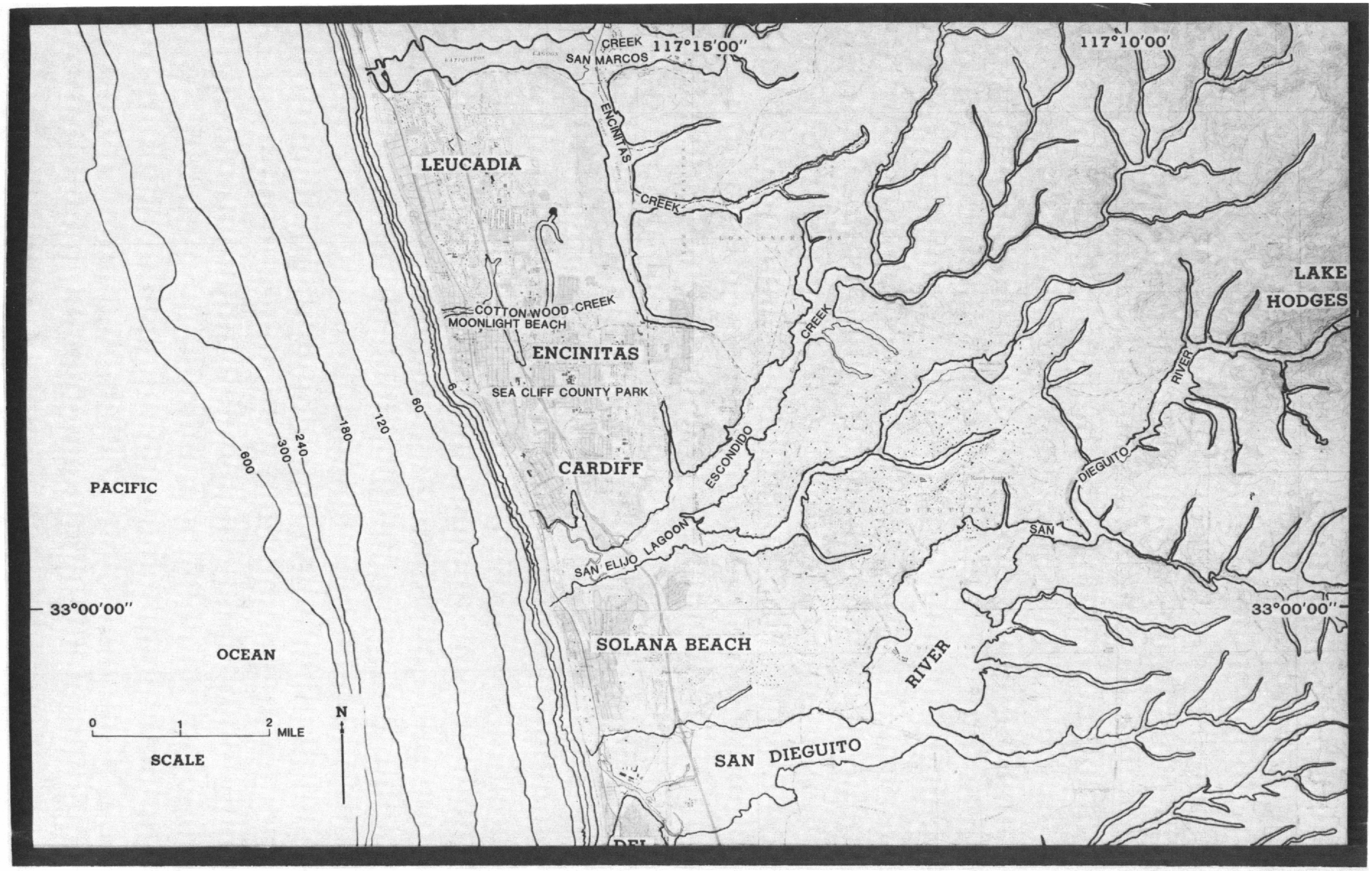


Figure 74. Location map of Batiquitos Lagoon south through Leucadia, Encinitas, Cardiff, and Solana Beach to San Dieguito River. Note: Bathymetry in feet (figure from Kuhn and Shepard, 1984).

was apparent (Figure 75). A compilation of all maps between 1880 and the U.S. Coast and Geodetic Surveys (filed in August 1891) indicate significant coastal change.

5.277 Examination of 1885 through 1891 San Diego County Tax Asessors records of lands parcels located at and south of the mouth of Cottonwood Creek (Figure 74), Encinitas, indicate that the seaward property was devalued and land parcels directly increased temporarily in value (Figure 20). Evidently the slope angle was very gentle, possibly indicating the town was partially laid out on a former landslide (Figure 76).

5.278 In 1919, this section of coastline still exhibited a moderately gentle slope (Figure 77). Today the cliff is vertical at this location.

5.279 One half mile south, at the present site of Sea Cliff County park, numerous coastal changes have occurred since 1900. A photograph taken in 1905 (Figure 78) illustrates a cliff surface covered by former cliff failures and talus. Today the cliff face is exposed, stands vertical, with no talus present (Kuhn and others, 1987).

5.280 Looking south from the same location, a photograph taken in 1922 (Figure 79) shows the wide beach and landslide debris fronting the sea cliff. In 1958, a massive landslide occurred at a site located in the center of this photo (Kuhn et al. 1987).

5.281 In 1938, the Self Realization Fellowship, constructed a four story temple 35 feet from the bluff top edge in South Encinitas (Figure 47a). In the early 1940's following the intense rainfall and severe sea storm of December 23rd, 1940 and early January 1941, the temple was destroyed by a large frontal landslide (Figure 47b) (Kuhn and Shepard, 1979, 1984).

5.282 The cliffs along the section of Cardiff-by-the-sea showed little change when viewed in the 1890's (Figure 80). Significant erosion occurred when the blufftop was graded and removed in the 1960's.

5.283 The grading of the bluff tops, in many cases to the edge of the slope, initiates slope failures in the sea bluff and creates drainage avanues along which further surface runoff erodes the bluff-top edge and the bluff face. It has been observed that where the existing terrace deposits and soil profile are left intact and surface drainage is diverted, the bluff edge appears to erode very slowly.

5.284 Subaerial erosion processes which have accelerated erosion of these cliffs are as follows: 1) spring sapping by ground water along the cliff face which may initiate landslides; 2) surface runoff along street ends which flows

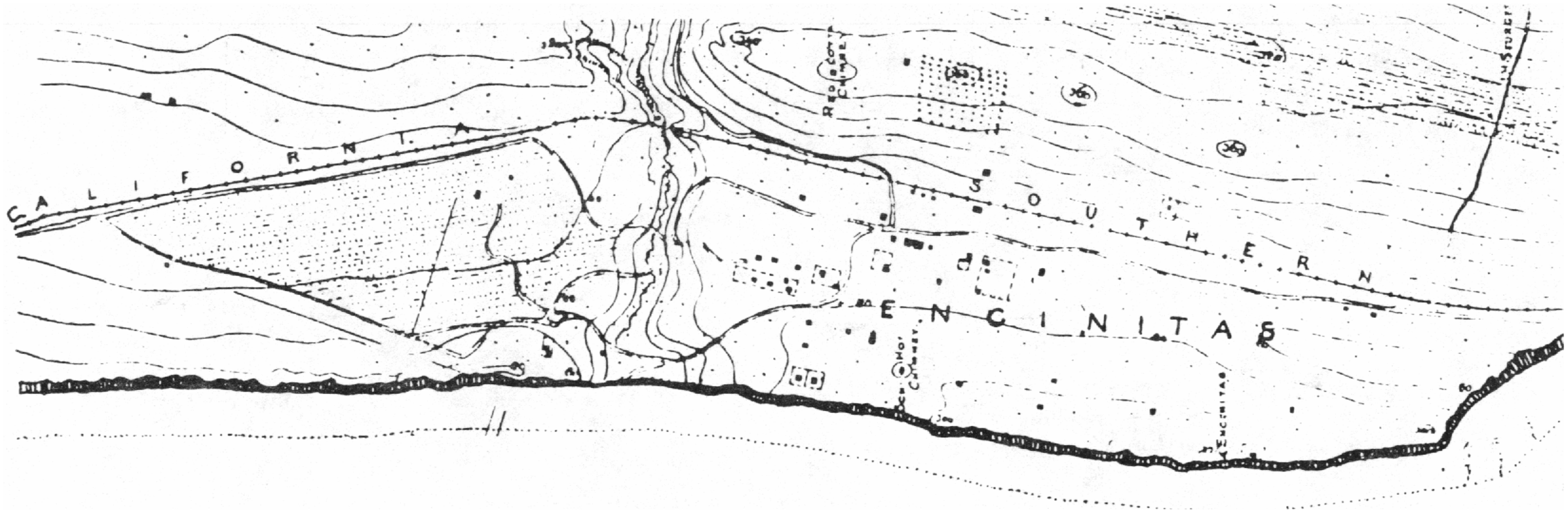


Figure 75. Map view of a section of Encinitas as surveyed by the U.S. Coast and Geodetic Survey during the late 1880's. Their work began in 1887 and continued during stormy years until 1890; map was filed in the survey Archives in April 1891 (from U.S. Coast and Geodetic Survey Topographic Map No. T-1898).

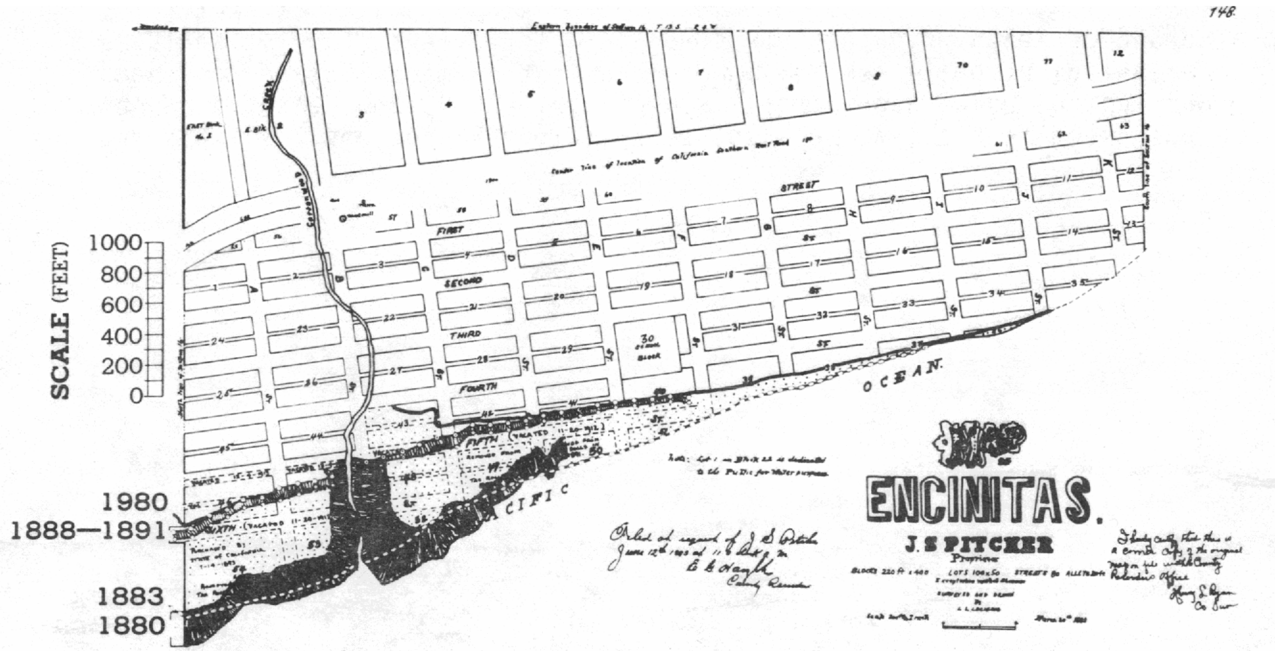


Figure 76. 1883 San Diego County subdivision map of Encinitas, California. Seaward hatchured data is from California Southern Railroad Topographic Survey, 1880. White dashed line is as per 1883 subdivision map and California Southern Railroad location map (January 1, 1883), 1888-1891 lines are U.S. Coast and Geodetic Survey, and solid block line further inland is approximate 1980 bluff top. Note: Over 600 feet of retreat occurred between 1883-1891.

Figure 77. View looking north along the cliffs at Encinitas California in 1919. Note: The gentle slope. The cliffs are presently vertical at this location (photograph by U.S. Geological Survey).

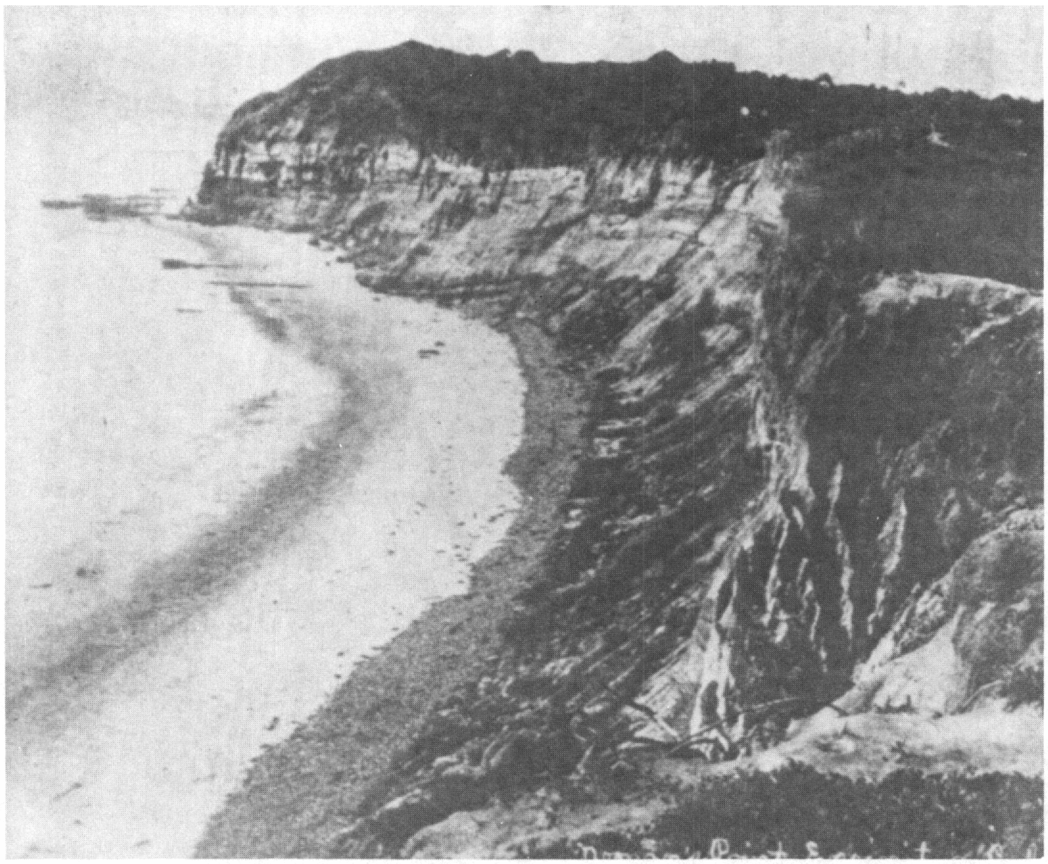


Figure 78. View at Sea Cliff County Park at Encinitas, California in 1905. Note: Extensive landslide material along cliff face (photograph courtesy of Ida Noonan Truax).

Figure 79. View looking southeast along the cliffs just south of the present site of Sea Cliff County Park, Encinitas in 1922. Note: Extensive landslide debris and talus along the base of cliff (photograph from Title Insurance and Trust Company Collection).

Figure 80. View looking north along the cliff at the present site of San Elijo State Park in south Cardiff-by-the-Sea California in 1912. Note: The extensive talus which covers the cliff base (photograph from Title and Trust Insurance Company Collection).

down the cliff face; 3) erosion of the cliff face as a result of heavy rainfall; 4) collapse of storm drains designed to carry surface water runoff away from cliff faces.

San Dieguito River to Penasquitos Lagoon

5.285 Morphology. The City of Del Mar is located partially on an inland coastal terrace and partially on a delta bordered by a low-lying beach to the north (Figure 81). It is adjacent to the flood plain of the San Dieguito River. The coastal terrace has a seaward margin with vertical to near-vertical cliffs consisting of weakly-cemented, highly-fractured, ancient lagoonal strata of Eocene age. These strata are capped by Pleistocene sand that is well cemented by iron-oxide, tends to stand vertically even when undercut, and appears to be more resistant to erosion than the underlying Eocene beds. Numerous canyons and gullies have been cut inland and upland from the first coastal terrace.

5.286 Coastal Changes. Erosion of the cliffs along this coastal segment has not contributed appreciable sediment to the beach during the period studied.

5.287 The U.S. Coast and Geodetic Survey mapped the topography and bathymetry of this coast beginning in 1887 and finished in 1890. The maps were filed in the U.S.C.G.S. Archives in April 1891. The mapping took longer than was the norm as a results of flooding and heavy rains (U.S.C.G.S. Report to the Superintendant of the Survey (1890).

5.288 Examination of these early U.S. Coast and Geodetic Survey topographic field sheets was made and maps were compared with the U.S. Geological Survey of 1953 (Scale 1:24000). No appreciable change in the slope toe or base of cliff is evident at this scale.

5.289 Subaerial erosion processes that have accelerated cliff retreat along this coastal segment are the following: 1) recent urbanization inland has caused an increase in the groundwater table; this, in turn, has initiated landslides and blockfalls along the cliffs since 1978; and 2) during periods of heavy rainfall, surface runoff along street ends erodes the cliffs causing landslides.

5.290 The San Diequito River is one of the largest rivers in San Diego County. Major floods have occurred in past years, and the most recent was in March 1938. At present, two water storage dams, Lake Hodges and Lake Sutherland, are located on the river. The majority of usable beach sand and other sedimentary material does not reach the coast today, but is deposited behind the dams. The State of California Department of Water Resources (1966) estimates that the sediment thickness of the flood plain varies from 100 to 150 feet. River flooding between the 1880's and 1930's contributed large quantities of sediment which widened the beach and temporarily slowed erosion of the cliffs at Del Mar.

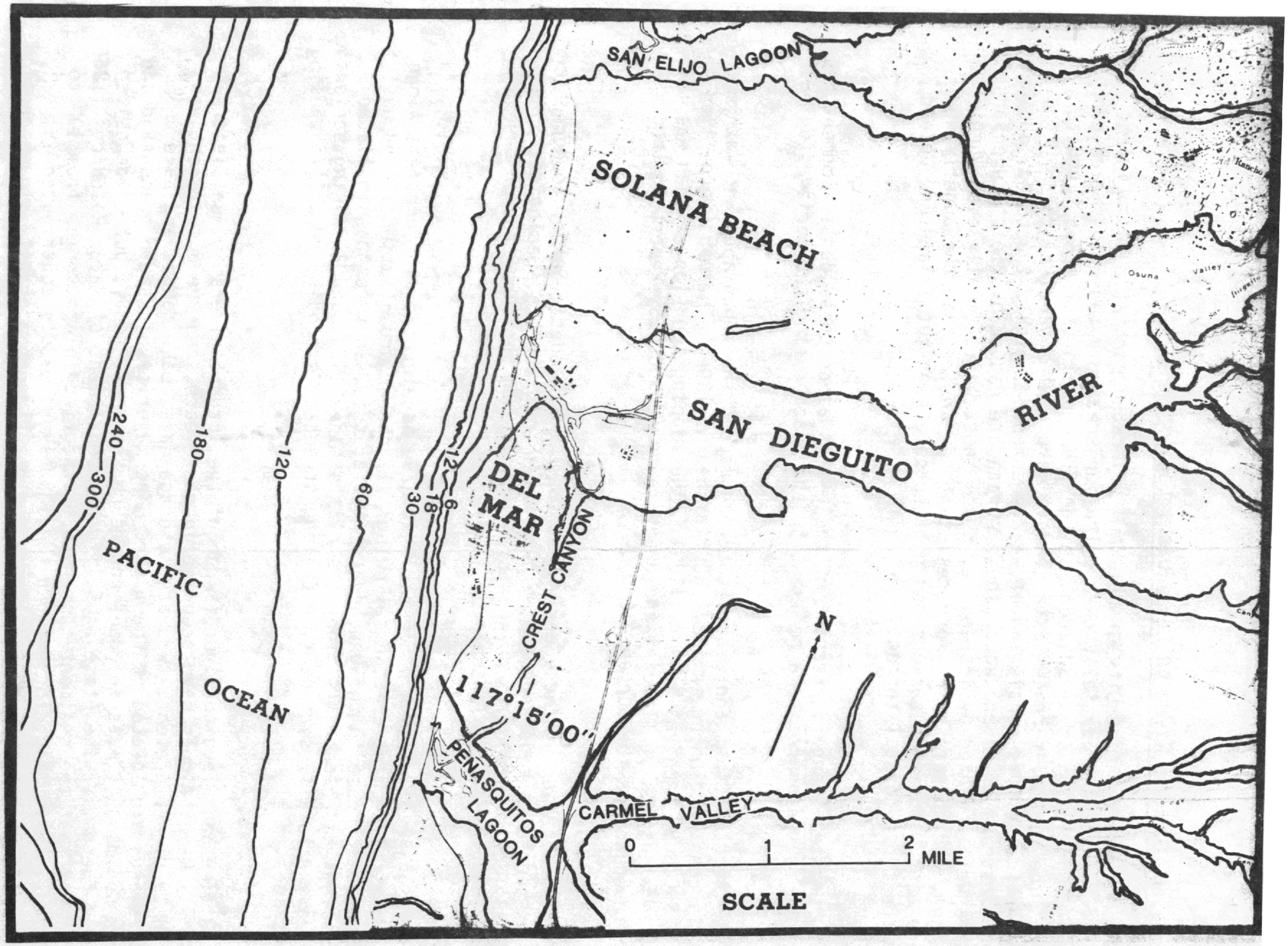


Figure 81. Location map of Del Mar and vicinity. Note: Bathymetric contours in feet (from Kuhn and Shepard, 1984).

5.291 Del Mar became a town in 1885. No houses existed on the barrier beach at Del Mar during the 1880's (Figure 82). The settlers were aware that frequent flooding on the San Dieguito River could destroy houses or farms located on the beach or floodplain.

5.292 Only two wooden buildings were located on the beach along South Del Mar. A large bathhouse was constructed on a former landslide at 12th Street (Figure 83). At the foot of 10th Street, a glass-enclosed, wooden wading pool was designed to let sea water in and keep out the dreaded "Sting-a-ray" (Figure 84). Both structures were broken up during severe storms of the last century.

5.293 Prior to 1900, the Santa Fe Railroad line was located a block inland from the bluff. In 1910, the railroad relocated the route seaward because the grade inland was too steep, and also to accommodate the growing City of Del Mar (Santa Fe Railway Co., 1978). To create a more level right-of-way, the bluffs were steam shoveled and dynamited (Figures 85, 86). Since then, several trains have crashed to the beach as a result of undercutting of the cliffs both by waves and by runoff from streets ending at the bluff, and because of increasing subsurface groundwater pressures (Kuhn and Shepard, 1984). The most recent train derailment was on January 1, 1941, when the bluff collapsed (Figure 46). This specific location is particularly susceptible to erosion, as surface water, especially during wet years, flows directly down the street end, ponds to the east of the tracks and then exits the cliff face along impermeable clay layers which initiate landslides.

5.294 In the last century natural cobble rock barriers existed across the mouth of estuaries lagoons and river mouths. A most extensive one described as more than 40 feet in height existed across the mouth of Soledad Creek [Penasquitos Lagoon] directly south of Del Mar. Judge Benjamin Hayes in his emigrant notes (1872) marveled at this coastal feature and noted:

> "Perhaps the greatest curiosity is the high wall composed of small rocks, which at some day, long ago, the dashing waves have built up, extending the whole length of the beach, across the mouth of the valley, making sort of a natural breakwater, through which now the sea can pass only at the northern side, in the Spring tides and storms to mingle with the fresh water of the creek."

5.295 In 1889, the U.S. Coast and Geodetic Survey indicated that the California Southern Railroad had installed a "beach shingle railroad siding" onto and across the extensive cobble barrier in order to sell the beach rocks to make streets in the City of San Diego (Figure 87).

Penasquitos Lagoon to La Jolla Submarine Canyon

5.296 Morphology. The spectacular cliffs along this section of the coast reach a maximum height of over 350 feet and extend from Sorrento Valley (Penasquitos Lagoon) to La Jolla Shores. These cliffs consist of ancient

Figure 82. 1889 U.S. Coast and Geodetic Survey map of Del Mar and vicinity (from U.S. Coast and Geodetic Suvey Topographic Map No. T-2014.

Figure 83. Bathhouse located on the beach at Del Mar in 1891 (photograph from Title Insurance and Trust Company Collection).

Figure 84. View of glass-enclosed wading pool which was located at the foot of 10th Street, Del Mar during the 1890's (photograph from Scripps Institution of Oceanography Archives).

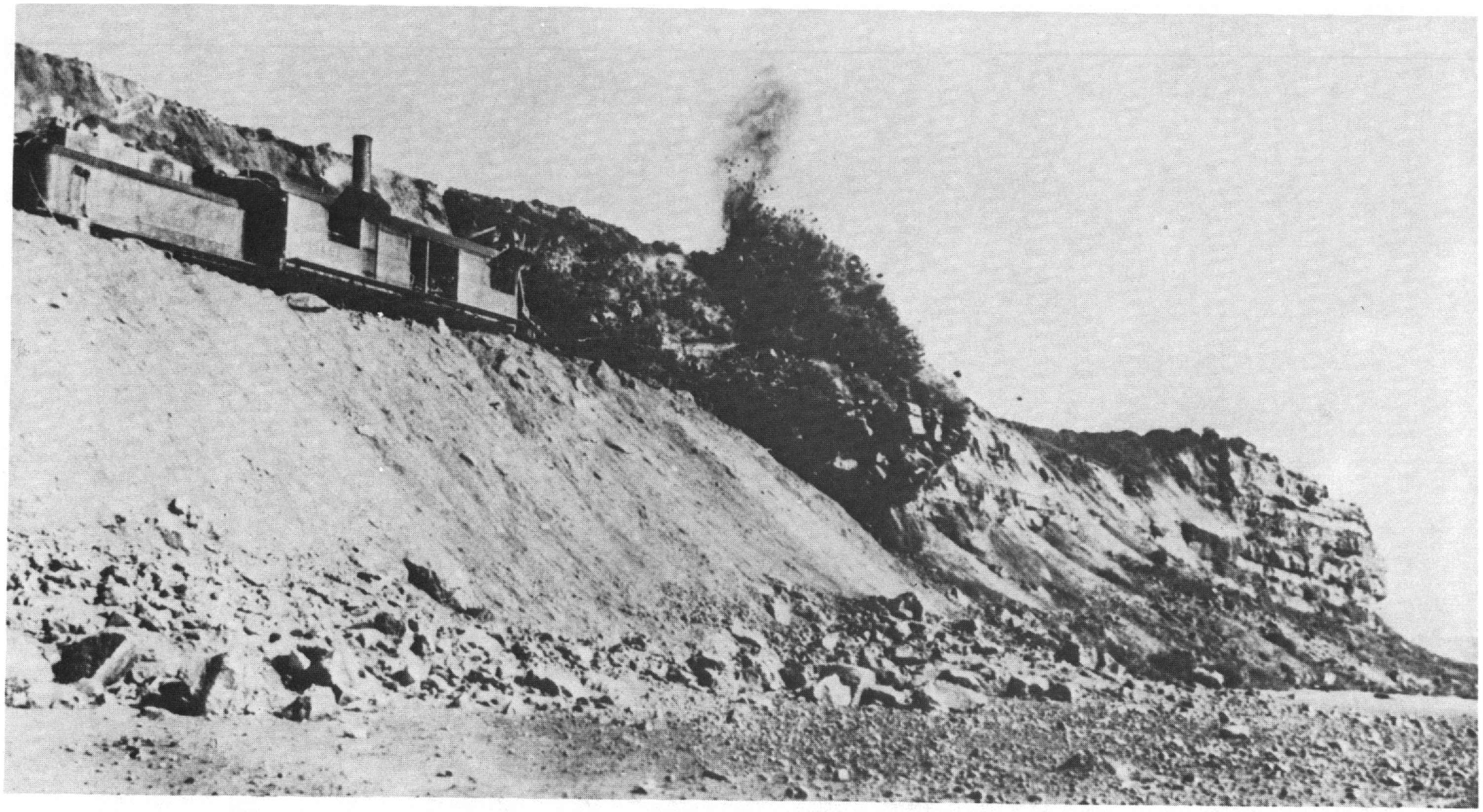


Figure 85. February 1910 view looking southeast along the cliffs at Del Mar showing construction of railroad bed (photograph by Santa Fe Railway Company).

Figure 86. February 1910 view looking north along the cliffs at Del Mar showing construction of railroad bed (photograph by Santa Fe Railway Company).

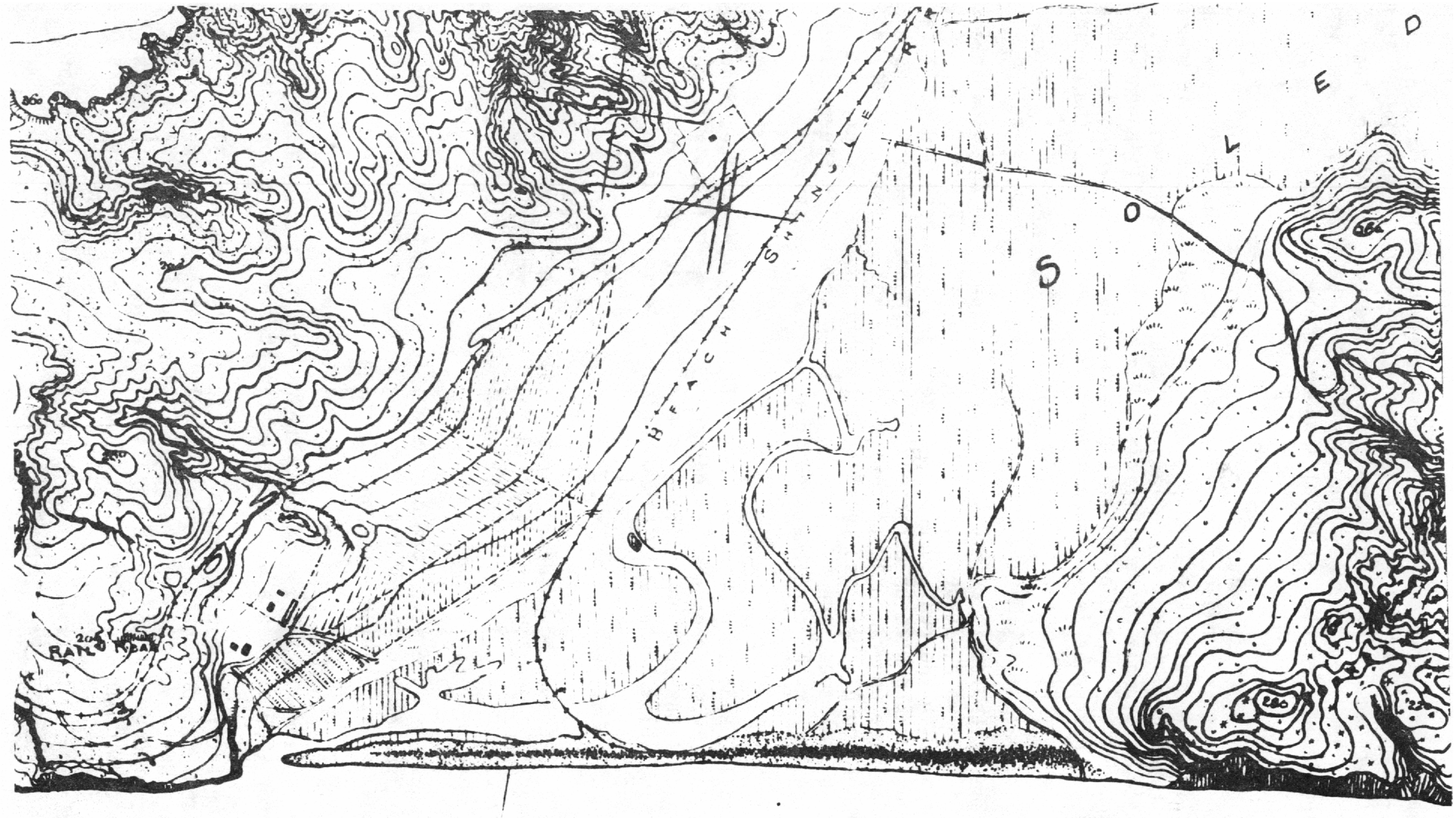


Figure 87. 1889 map view of Beach Shingle Railroad siding which was installed onto a great cobble barrier across the lagoon south of Del Mar. Cobbles were removed and became street-construction material in San Diego (from U.S. Coast and Geodetic Topographic Survey No. T-2014).

lagoonal marine and terrestrial sediment of Eocene age with a capping of iron-oxide-cemented terrace deposits of Pleistocene age (Figure 88). At the south end, a volcanic dike of Miocene age cuts the Eocene sediment, and south of the dike an infilled embayment of late Pleistocene sediment occurs, which includes iron-oxide-cemented alluvial sand and gravel.

5.297 The La Jolla coast, with its northern boundary at the original Scripps Institution campus (now expanded considerably to the north), extends along the alluvial cliffs, now almost entirely guarded by seawalls, to the old barrier beach that historically enclosed a lagoon at the mouth of Hidden Valley. The lagoon now consists only of an artificial pond at the La Jolla Beach and Tennis Club, but is low enough that it occasionally floods during heavy rains, temporally drowning what is now a completely built-over area on the marshy soil.

5.298 To the south, rocky cliffs with terraces rise above this low area and are bordered by a wave-cut terrace exposed at low tide. There is a right-angle bend in the coast where these terraces terminate and Point La Jolla extends seaward with an escarpment based with deep reentry caves extending far back under the 40 foot high terrace which terminates at La Jolla Cove. Farther south, the point recedes, but continues to be rocky with relatively low terraces, and is indented by a few coves with steep, sandy beaches which derive their coarse sand from the local cliffs.

5.299 <u>Coastal Changes</u>. Erosion of the cliffs along Torrey Pines State and City parks contributes appreciable sediment to the beach locally from a combination of landslides and cliff face and canyon erosion. The cliffs along Scripps and La Jolla Shores also has contributed sediment during specific storm periods.

5.300 The U.S. Coast and Geodetic Survey was mapping this section of coast between 1889 and 1890. The survey field sheet notes relating to the map showing the topography southward from San Dieguito Valley [to La Jolla] indicated that:

> "The Coast is generally formed of precipitous bluffs, much broken and bearing evidence of "slides" during winter storms when the soil becomes saturated with water and top heavy".

5.301 Marcos Hanna (1926) was mapping the geology of the La Jolla Quandrangle in the stormy 1920's. Hanna was aware of recent coastal erosion and noted:

> "The most effective agent modifying the land in the La Jolla Quadrangle at present is the ocean. Cliffs have been formed to some extend throughout the western border. The rapidity with which this eastward cutting is progressing is indicated by the lack of talus at the bottom of many of the cliffs. During the winter great blocks of the cliffs slide into the ocean, only to be removed almost immediately by the waves. Some three miles south of the mouth of

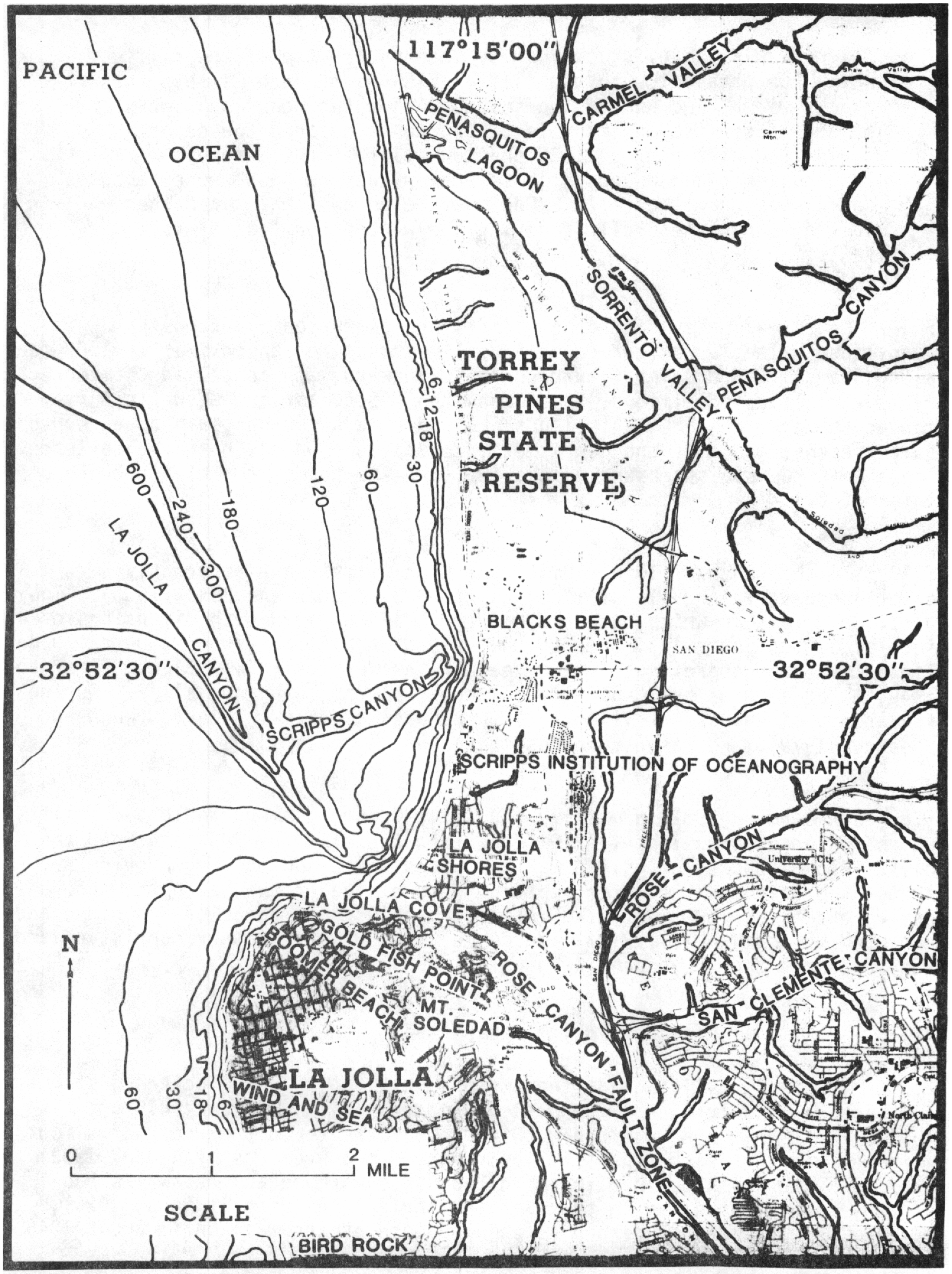


Figure 88. Location map of Penasquitos Lagoon (Sorrento Valley) southward through Torrey Pines State Park, Scripps Institution of Oceanography, La Jolla Shores, and north La Jolla (from Kuhn and Shepard, 1984).

> Soledad Valley many cracks can be seen on the top of the cliff, which run parallel with the cliff. With each winter's rain these cracks widen, and become lubricated with water, causing blocks several feet wide and many feet long to slide into the ocean. During the winter of 1921-22 the low cliff at the Scripps Institution receded enough in several places to cause worry about a few houses near the cliff. One must be on constant guard when walking under these cliffs during the winter for fear of rock falls."

5.302 South of Torrey Pines, the cliffs are disturbed by extensive landslides. The largest of these landslides measures approximately 1700 feet along the cliff and several hundred feet landward, and is called the Torrey Pines Park landslide (Figure 89). When the U.S. Coast and Geodetic Survey mapped the area in 1889, this landslide and others to the south appeared to be quite recent, as talus and debris extended far out on the beach. The Torrey Pines Golf Course is presently located along the top of the bluff, south of this point.

5.303 To the south of Torrey Pines the high cliffs have apparently experienced very large landslides, as noted by Summer and Ross (1930). They describe a failure which occurred between 1917 and 1922 with dimensions of 450 feet along the shore, 175 feet to the base of the cliff (75 or 100 feet wider higher up), and approximately 200 feet of the vertical cliff face. Prior to 1940, a large talus build-up allowed access to this hanging valley. During the storms at the end of 1940, this talus was completely removed (Kuhn and Shepard, 1979), and was not reconstituted until about 1970.

5.304 In January 1982, a massive landslide occurred along these same cliffs, which measured approximately 750 feet along the cliff by 280 feet into the cliff (Figure 90). This slide carried material including large boulders across the beach to the water, cutting of one side of the beach from the other, except at low tide. The material consisted of acres of sandstone and amounted to as much as <u>1.8 million cubic yards</u> of sedimentary debris, a large future source for the beach (Kuhn et al. 1987).

Alluvial Cliffs Near Scripps Institution

5.305 The first buildings of the Scripps Institution were located just a few feet inside this terrace (Figure 91). Apparently the builders did not realize that this area was subject to rapid retreat, on the order of a foot or more per year, as was established by repeated measurements (Vaughan, 1932). This was actually known earlier than Vaughan's work because seawalls had already been constructed in front of the Scripps buildings (Hanna, 1926); nonetheless, retreat continued north and south of the wall until about 1946.

5.306 The erosion was found to be related to the fact that the sand beach was several hundred feet wide at low tide in the summer and was subject to depletion during winter storms (Shepard and Grant, 1947). Generally the

Figure 89. 1975 view of Torrey Pines landslide which measures approximately 1700 feet along the cliff (photograph by F. Shepard).

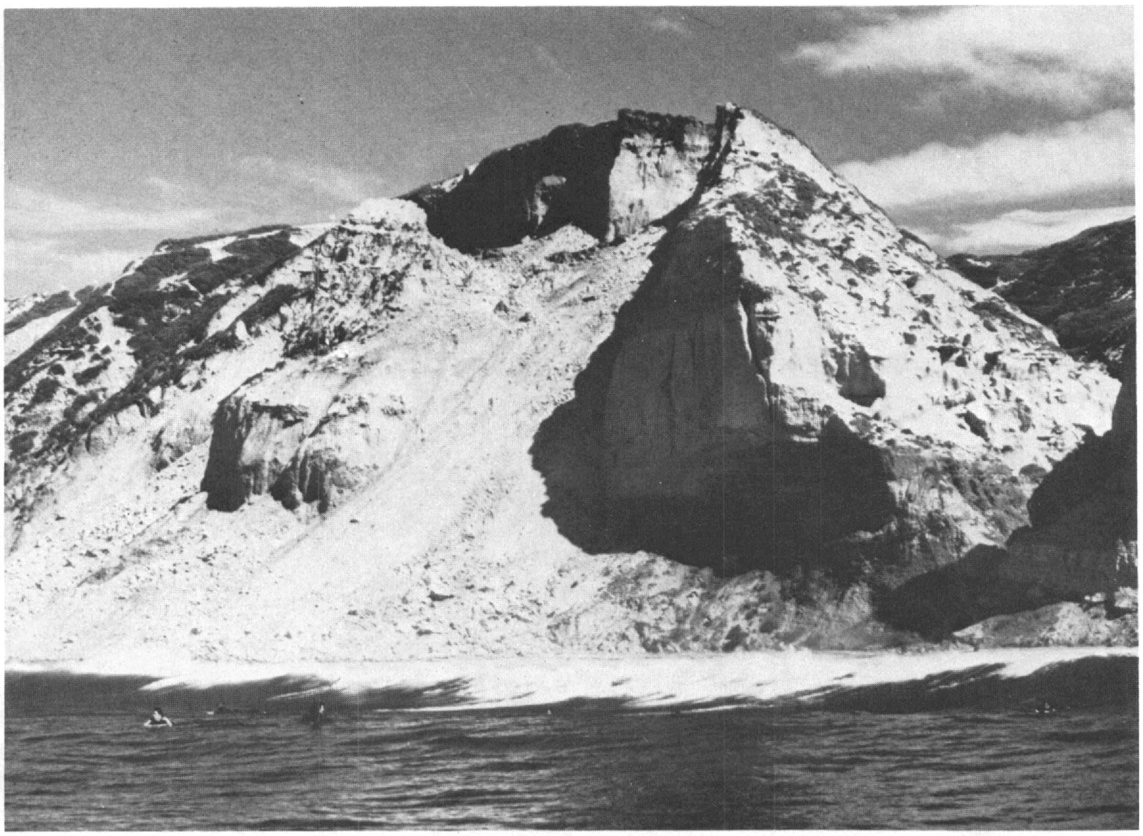


Figure 90. 1982 landslide at Blacks Beach, north of Scripps Institution of Oceanography (SIO). Note: Recent slide material on the beach and the fresh vertical scarp behind the slide (photograph by Gerry Kuhn).

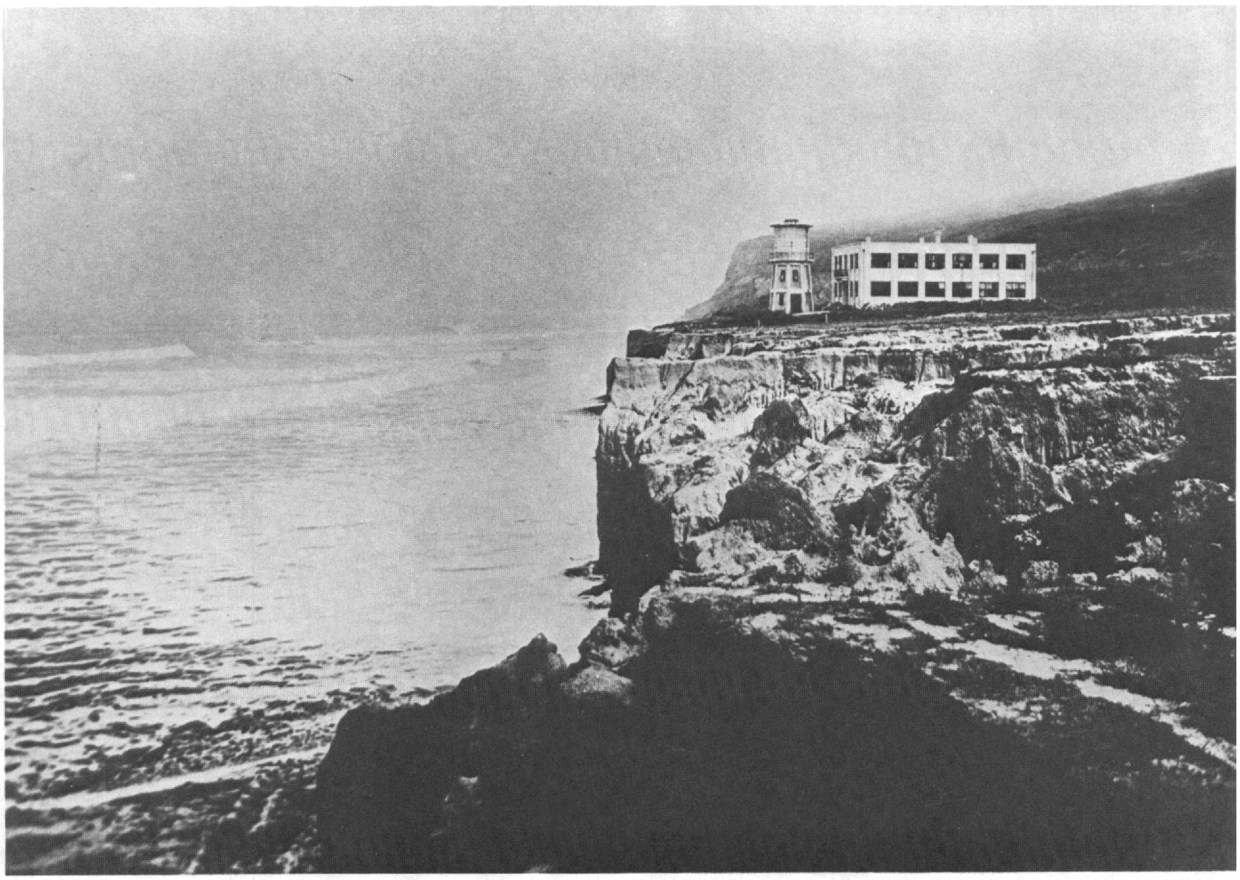


Figure 91. View along the vertical cliffs at Scripps Institution of Oceanography in 1910 (photograph from F. P. Shepard Collection).

erosion began as a series of storms exposed underlying gravel and sometimes the underlying semi-consolidated alluvial formation (Figure 92). During late winter storms, this allowed the waves, with the help of cobbles, to undercut the alluvial cliffs and thereby produce the annual retreat (Kuhn and Shepard, 1984).

5.307 Shepard and Grant (1947) stated that the cliffs at this location had retreated (when averaged) at approximately a foot a year during the 1930's and 1940's.

5.308 Beginning in 1946, however, the storms became less violent, and the beaches were not appreciably cut away in the winters, so the smaller waves that reached the cliffs were not capable of undermining them. Instead, over the next thirty years, most of the bluffs gradually became less steep, and vegetation became well established on the slopes. Only an occasional storm did any cutting, and then it was at the cliff base (Kuhn and Shepard, 1984).

5.309 In 1975, Hannan reviewed available records and surveys between 1912 and 1975. His study indicated that these cliffs retreated as much as 56 feet during that period. However, he indicated that 54 feet of coastal change actually occurred between 1912 and 1954, with no apparent change until the cliff top was graded in 1978 (Kuhn and Shepard, 1984).

5.310 La Jolla Canyon has steep sides, a vertical headwall, and is located at the southern end of the Oceanside Littoral Cell. It extends for 33 miles seaward in a general southwest direction and enters San Diego Trough 27 miles off the coast at a depth of 3600 feet (Figure 93).

5.311 An interesting feature of La Jolla Canyon is the effect it has on the waves on the long beach at La Jolla Shores. The waves are almost always much smaller at the head of the canyon, due to wave divergence, as the crests move up the canyon. Conversely, they are much larger at the north end of the beach where the waves converge, so there may be 2-foot breakers at the canyon head and 10-foot breakers in the northern convergence, half-a-mile upcoast. This is also true for the southern convergence.

<u>La Jolla Coastal Segment</u>

5.312 <u>Morphology</u>. To the south of La Jolla Shores, the seaward continuation of Mt. Soledad is encountered, where the City of La Jolla is located (Figure 88). The relatively low cliffs just south of the shores are of Cretaceous sandstone, and are bordered seaward by a wide wave-cut terrace that is exposed at low tide. The tilted strata exposed on the terrace give the appearance of a series of small hogbacks resulting from the erosion of the tilted strata (Kuhn and Shepard, 1984).

5.313 Just south of the tidal terrace, a fault coast continuation of the north scarp of Mt. Soledad occurs. In fact, this terrace rather clearly dips

Figure 92. 1936 view of low-lying alluvial cliffs at Scripps. Cliffs were retreating at that time at a rate of about 1 foot per year (photograph by U.S. Grant IV).

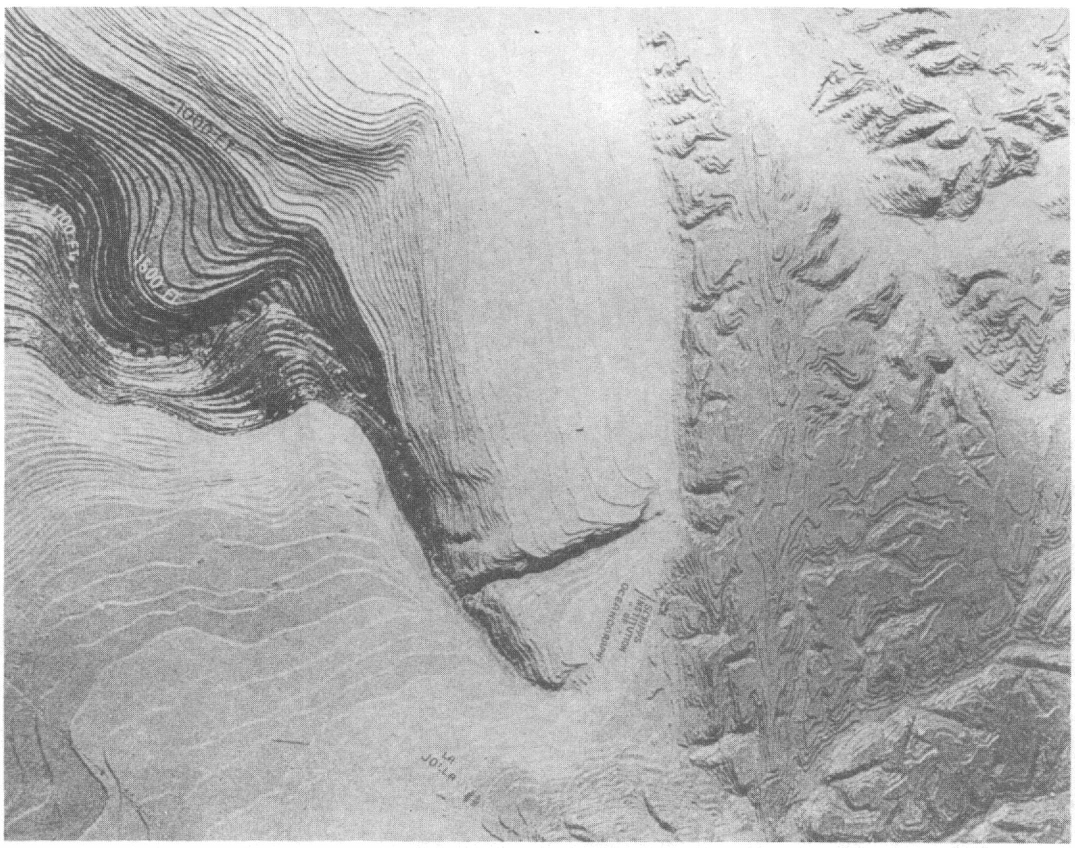


Figure 93. Locations of the La Jolla and Scripps submarine canyons offshore at La Jolla, and their relation to the land canyons (from Shepard and Emery, 1941).

down at its southern end before encountering the east-trending sandstone cliffs of Cretaceous age at its southward termination. The cliffed north side of Point La Jolla has deep caves that were formed as a result of a combination of wave erosion and solution of the sandstone cement by groundwater.

5.314 Coastal Changes. Erosion of the cliffs along La Jolla, for the period studied, has contributed negligible sediment to local beaches.

5.315 Examination of the early U.S. Coast and Geodetic Surveys topographic field sheets (1889) was made and comparison was made with the U.S. Geological Survey (1953) (Scale 1:24000). No appreciable change in the slope toe of base of cliff is evident at this scale.

5.316 Erosion of these cliffs is an interesting problem. Examination of the exposed formations and their concretions at the west end of the bluffs, and comparison of the present state with photographs circa 1900, shows a most conspicuous lack of appreciable erosion (Figures 94a, 94b). One arch at Goldfish Point has shown very little change since 1908 (Kuhn and Shepard, 1984). The same is true of some massive boulders of concretionary appearance a little to the east, near La Jolla Cove, which are apparently perched on the edge of a rock terrace exposed to activity of large converging waves formed by Alligator Head. On the other hand, looking at the cliffs farther to the east, there has been an obvious rock fall since the old photographs were taken. The bluffs have retreated locally more than 10 feet. Furthermore, old pictures of the cove, to the west of the cliffs, show decided changes in the well-known arches which existed in the early part of the century, and which were partially reinforced with cement in recent years. They finally collapsed, the last one falling in 1978 (Figure 95a). The outer part of Alligator Head has also changed since the early photographs, taken around 1870 (Figure 95b), but most of the relatively straight, rocky coast extending toward the Children's Pool has had little erosion since the 1930's.

5.317 Boomer Beach, just south of Alligator Head, is interesting to watch for seasonal changes. It consists of a coarse sand beach with steep frontal slope during summer months, but with the first winter storm, the sand is washed away to expose underlying bounders (Figure 96a). The sand is apparently partly carried to the south, forming narrow beach fringes, and some is carried seaward. However, with the onset of south-approaching waves and summer, the sand returns to Boomer Beach and the narrow fringes to the south disappear (Figure 96b).

5.318 At the Children's Pool, also known as Casa Pool, there is a man-made jetty built out from a rock point, and partly enclosing a cove. It was thought that by putting large holes in the south end of the jetty, any sand that was carried into the enclosure could be washed through, keeping the pool open. This did not work. The holes soon became blocked and the pool was filled with sand, leaving only a narrow semi-circle of water at the north end. Thus it has to be cleared-out occasionally when the sand level is reduced on the south side of the wall.

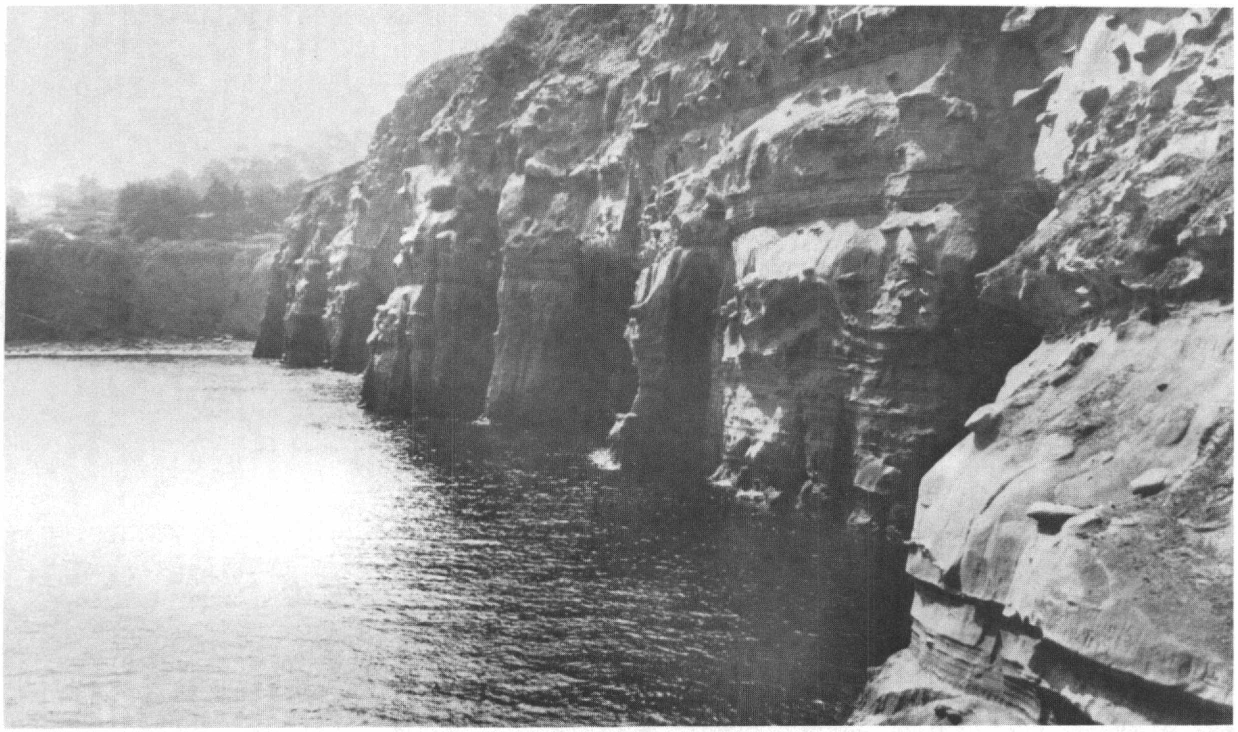


Figure 94a. 1916 view looking east at Goldfish Point, La Jolla. Note: Unique development of caves for this part of the coast. They have presumably formed through a combination of marine and solution erosion (photograph from SIO Archives).

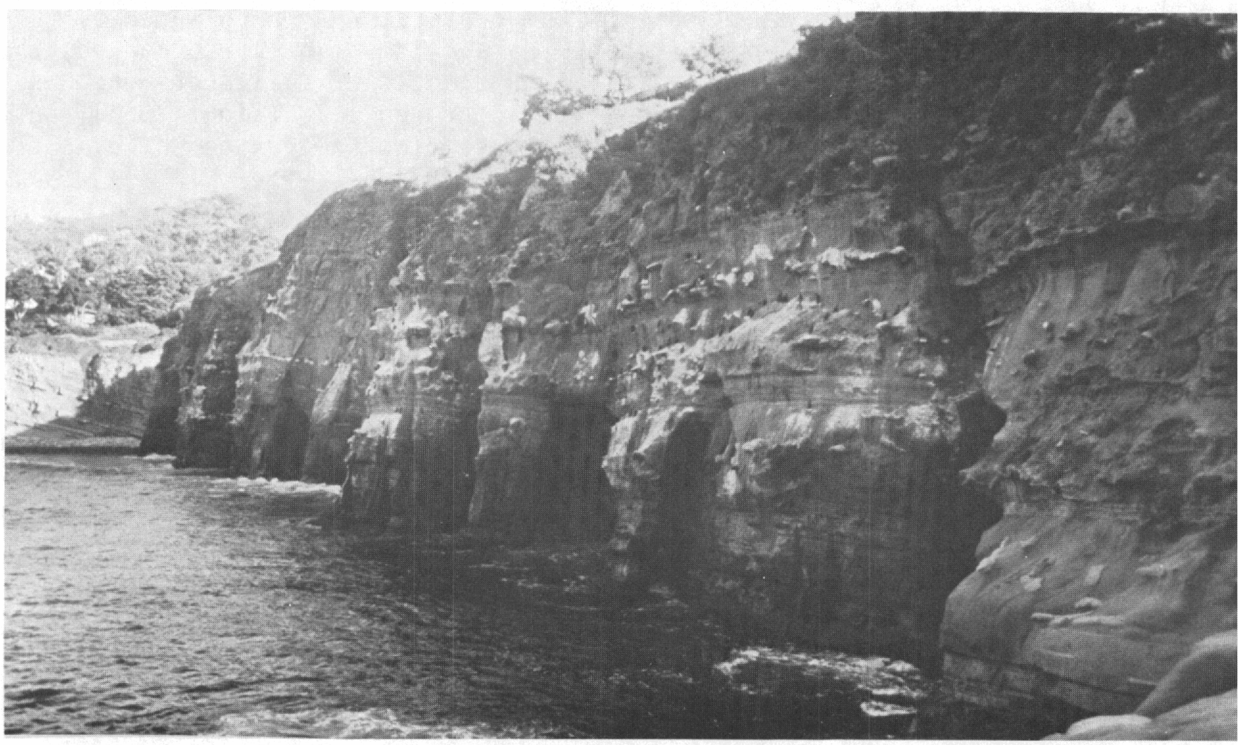


Figure 94b. 1978 view of same site as 94a. Note: Very little change is evident (photograph by F. Shepard).

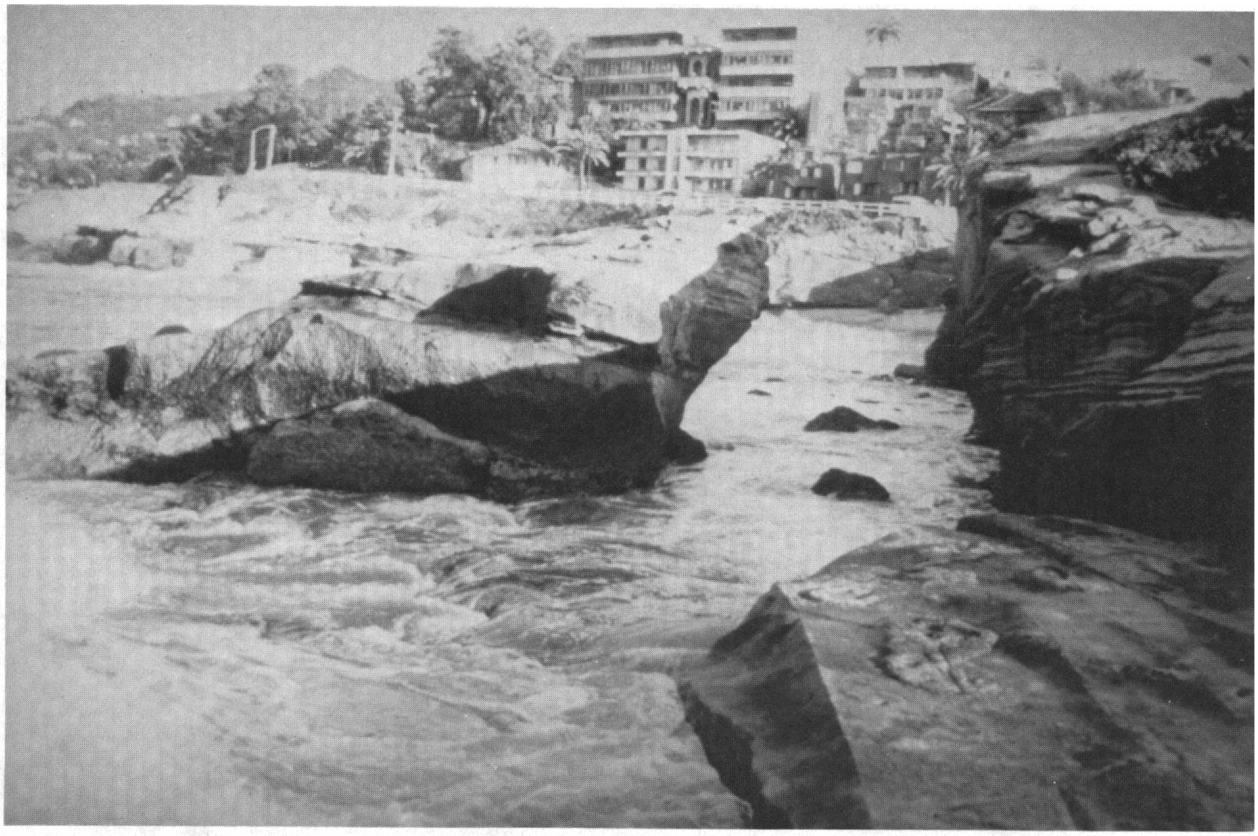


Figure 95a. 1978 view of Alligator Head Arch. Collapse of arch occurred during a storm in January 1978 (photograph G. Kuhn).

Figure 95b. 1870 view of Alligator Head Arch. Note: Many lineations and concretions are clearly identifiable in both this and the following photograph (photograph from F. Shepard Collection).

Figure 96a. Boomer Beach, taken sometime in the 1940s. This view shows winter conditions when heavy surf from the northwest has eroded the beach, and carried sand to the south, creating another, smaller beach at the left in the photograph (photograph by F. Shepard).

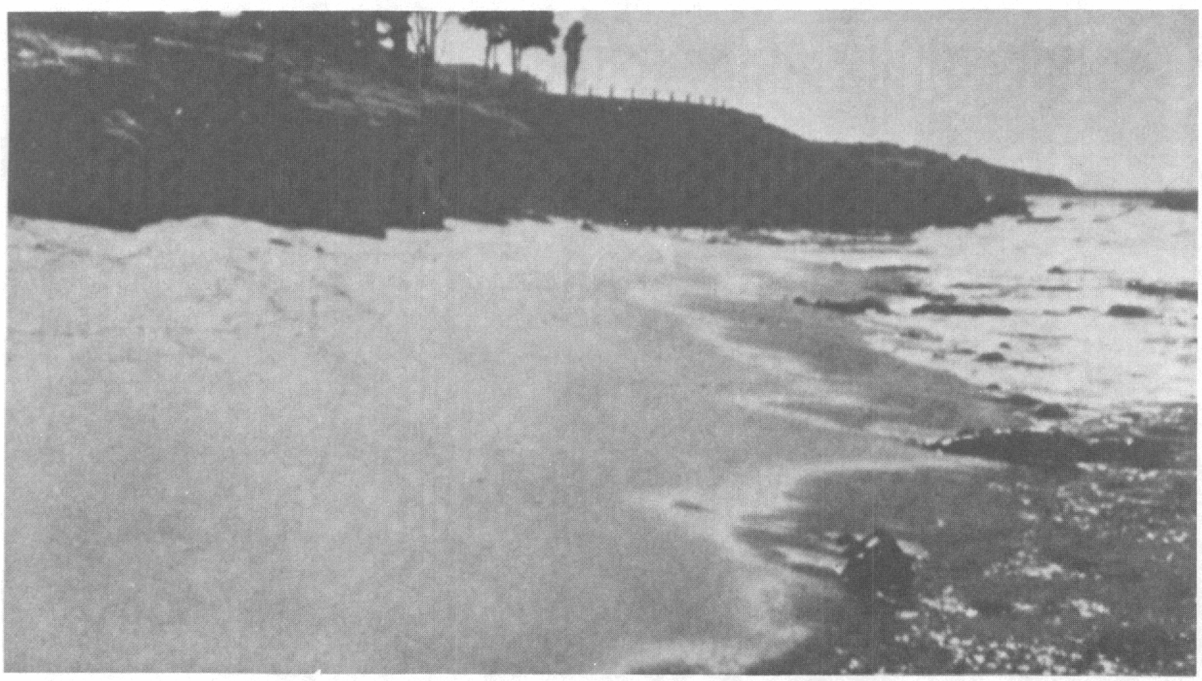


Figure 96b. Boomer Beach, west of La Jolla Cove, sometime in the 1940's. Seasonal change occurs as the result of different direction of wave approach and heavier winter surf. This photograph shows summer conditions; waves from the south have built a beach at the north end and have transported sand from the south end (photograph by F. Shepard).

5.319 Farther south, there was a rocky point with some breaks in its continuity, and a beautiful arch called Cathedral Rock existed on its west side in 1870 (Figure 97a). The arch collapsed in 1906, and when again photographed in 1934, the buttresses of the old arch were still standing, as well as other rocks, which have since gradually disappeared; every remnant of the arch is now gone (Figure 97b). Many sections of the partially-submerged rock point have been removed as well, so that the entire coast south of the Children's Pool has changed considerably since photography was initiated.

5.320 At Windansea Beach, photographs dating back to 1934 indicate that some interesting changes have occurred. There was a natural bridge, apparently cut in a surge channel, and exposed only when the sand was cut away from the formation during winter storms. This arch collapsed sometime in the 1950's. The sand is shifted to the south during the winter months, and to the north in the summer, as at Boomer Beach. Again, there is more sand during the relatively small waves of summer.

5.321 In south La Jolla, the cliffs and terraces are of much softer rock, and beyond the Bird Rock area they are largely alluvium. One house there had a porch extending out to the edge of a shale cliff, but in 1965 the porch collapsed when the underlying cliff failed. At Bird Rock, a stack stands above the tidal terrace, and shows little erosion during the past few decades, as documented through photographs. The low alluvial cliffs are actively eroding, but the rate has not been established.

Mission Beach Littoral Cell

5.322 The Mission Beach Littoral Cell (Figure 98) extends from Pacific Beach southward to the north jetty at the entrance to Mission Bay (Osborne, 1985), which is a distance of about 4 miles.

5.323 Morphology. The coastal lowland constituting Pacific and Mission Beaches rests on the former delta of the San Diego River. There is one slightly elevated portion at Crown Point, an extension of the La Jolla terrace. The alluvium extends almost to Crystal Pier in Pacific Beach, where it is replaced by a natural barrier bar built across Mission Bay. The community of Mission Beach, to the south, is built on this barrier, and has been protected from wave erosion by sea walls. The southern part of Mission Beach is a sand spit built across Mission Bay.

5.324 The San Diego River occupies a rather broad valley extending east and west, and entering Mission Bay, where it has deposited a considerable volume of alluvial material. The mouth of the river has been greatly modified by man (Figure 99a, 99b) to form a delta for the flat land between the northern margin of Point Loma and the low land around Old Town.

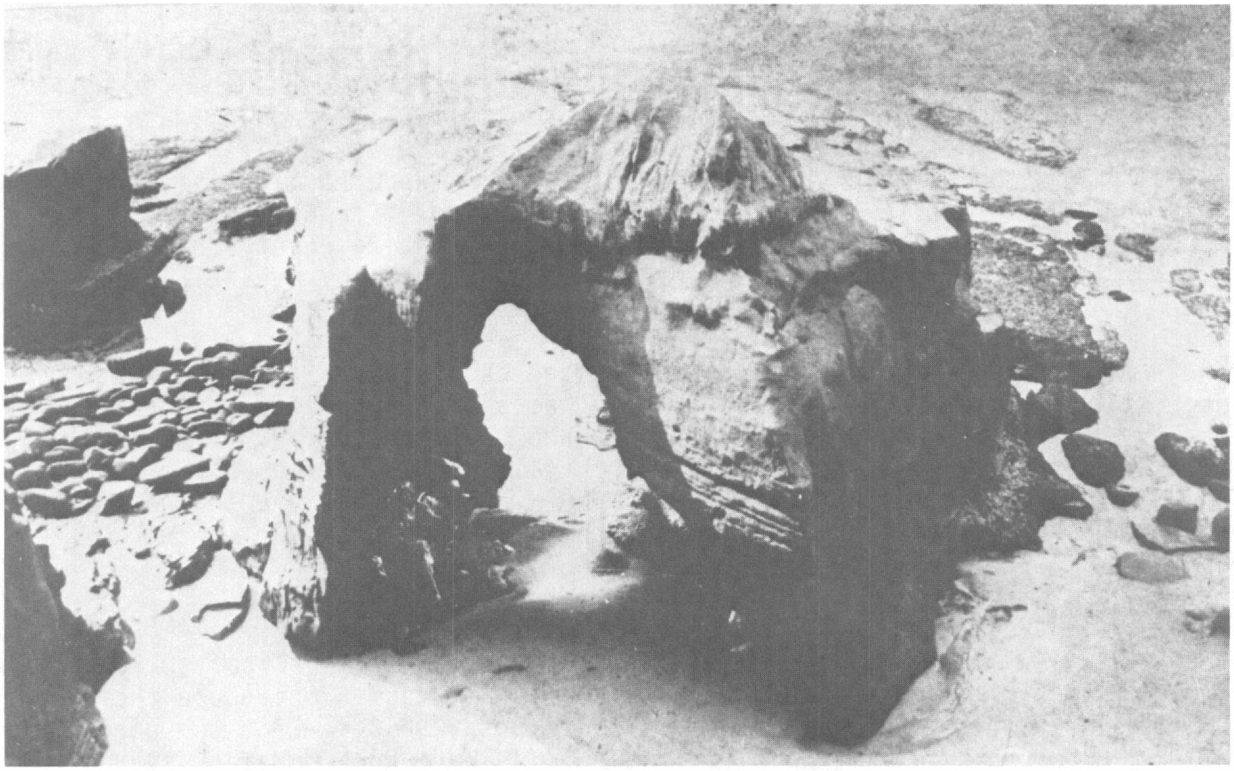


Figure 97a. 1873 view of Cathedral Rock Arch, La Jolla (photograph in F. Shepard Collection).

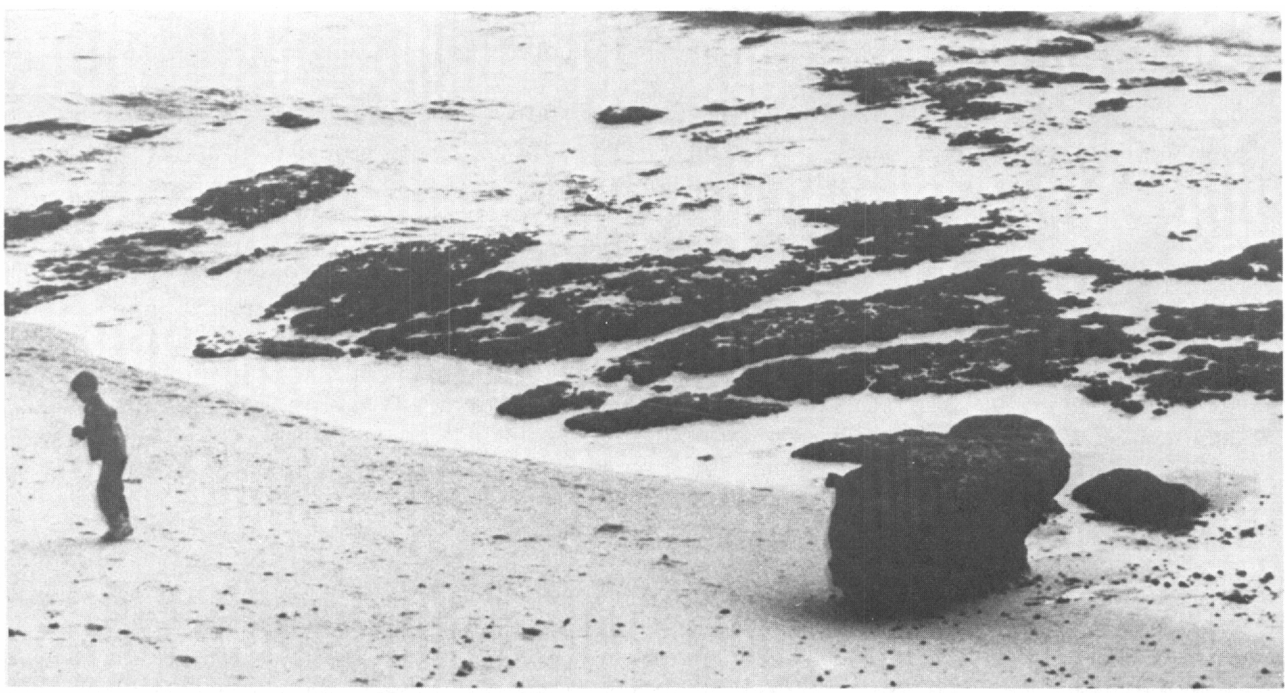


Figure 97b. October 1963 view of same site as 97a. A remnant is all that remains of the buttress of Cathedral Rock. By 1968 this remnant also had disappeared (photograph by F. Shepard).

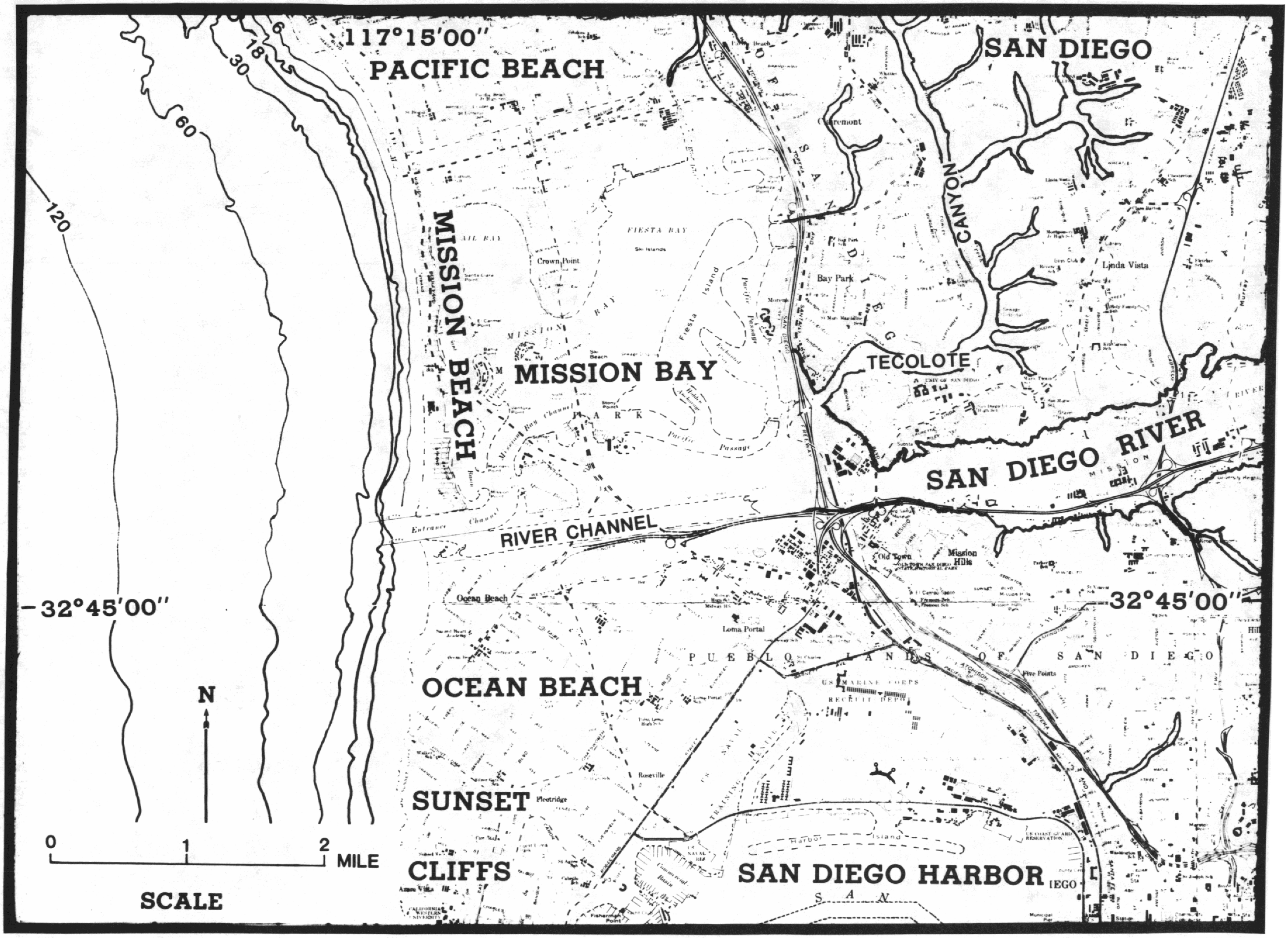


Figure 98. Location map of Pacific Beach and Mission Beach, San Diego Bay and San Diego River. Note: Bathymetric contours in feet (from Kuhn and Shepard, 1984).

Figure 99a. 1944 aerial photograph showing entrance to Mission Bay before jetties were built to maintain the boat channel (photograph by F. Shepard).

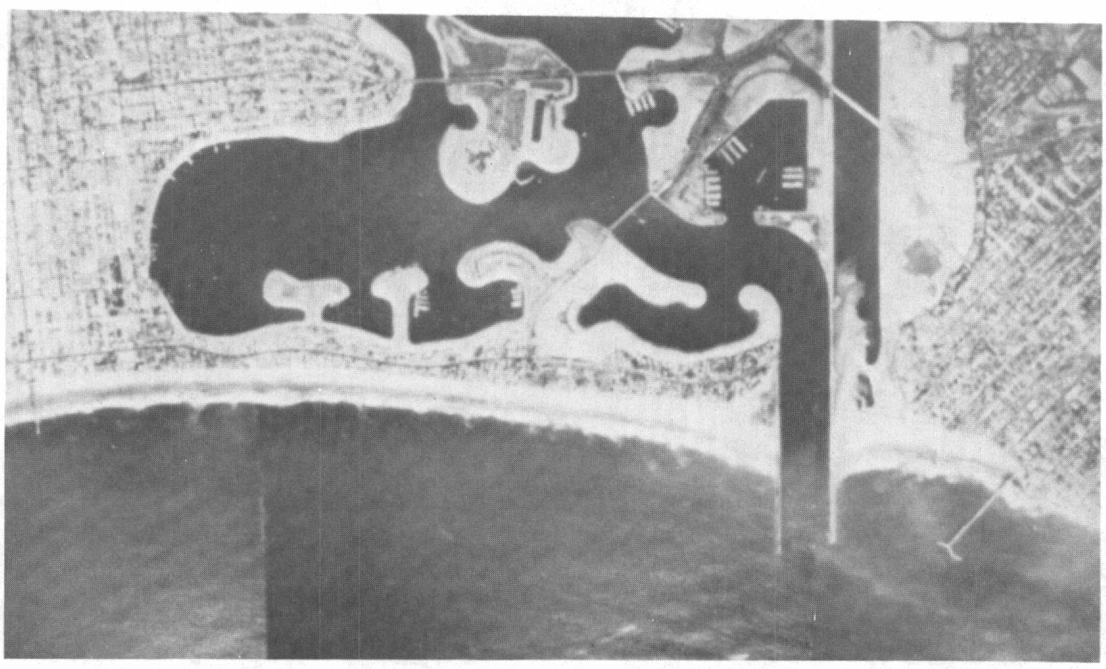


Figure 99b. 1968 aerial photograph of same location as 99a following construction of jetties at the mouth of San Diego River and entrance to Mission Bay. The area north of the jetties was extensively dredged to create a yacht basin and recreational facilities (photograph by U.S. Army).

5.325 The low cliffs north of Crystal Pier at Pacific Beach show that Subaerial processes were dominant over marine erosion during the late 1930's (Figure 100, 101).

Changes in Mission Beach and Mission Bay

5.326 The beach terminates before forming a complete barrier across the mouth of the bay. The tide is sufficient to keep the mouth open, and a flood channel has been built across the beach to carry floodwaters from Mission Bay to the sea. It is very doubtful whether this outlet could carry the volume of floodwater that could sweep down the valley in a repetition of the great floods of 1862, 1884, 1889, and 1891, or even subsequent smaller floods.

5.327 History of San Diego Harbor and River Channel Changes (From Kuhn and Shepard, 1984). San Diego is the oldest city on the west coast. It grew around the Mission San Diego de Alcala, founded by Father Junipero Serra in 1769 (Pourade, 1960). San Diego Harbor had been discovered more than 200 years earlier, in September 1542, by Rodriquez Cabrillo (Pourade, 1960). Presently the harbor is kept open by tidal currents, with the exception of a sandbar that has to be dredged from time to time. It is the best protected natural harbor on the southern California coast. Mission Bay, formerly called False Bay, was deep enough up until 1810 to allow even relatively deep draft vessels to enter (U.S. Congress), 1853.

5.328 During the early nineteenth century southern California rivers seem to have changed their courses periodically as the result of numerous floods. Prior to 1821, the San Diego River usually entered San Diego Harbor. In the fall of 1821, however, a flood changed the river channel in one night, and the greater volume of the flow was diverted into what was then known as False Bay, leaving only a small stream still flowing into the harbor (Hayes 1874). This flood was remarkable in that no rain fell along the coast. The river was later observed to flow into San Diego Harbor in 1849 and 1856, and the U.S. Coast and Geodetic Survey map of 1859 shows it to be flowing there once again. Because of the high deposition rate of the river, which threatened to ruin San Diego Bay as a harbor, the federal government diverted the flow into Mission Bay and built a levee embankment of earth extending from near Old Town to Point Loma in the fall of 1853 (Derby, 1853). Later that year, heavy rains caused the river to change course once again, washing out part of the levee and resuming its old course into the harbor (San Diego Herald, 1855).

5.329 The worst flood in this area was in 1862, appropriately called the Noachian Deluge, and was of special significance because it had a bearing on the Civil War. In San Diego, Mission Valley was inundated, and houses in lower Old Town were flooded when severe winds from a sea storm from the south backed the water up from the bay into the river (Pourade, 1964). This flood was very significant because it held its peak for over twenty-four hours.

Figure 100. View looking north along the cliffs at Pacific Beach January 1939. Note the gentle slope angle (photograph by F. P. Shepard).

Figure 101. View looking south along the cliffs at Pacific Beach in August 1936. Note: The gentle angle of slope. Crystal Pier is seen in background (photograph by F. P. Shepard).

5.330 In 1876, the levee was reconstructed, and no further diversions into San Diego Bay have occurred. Since then, a considerable volume of sediment has been added to the San Diego River delta in Mission Bay from occasional floods.

5.331 In 1935 El Capitan Dam was constructed twenty seven miles up the San Diego River; this reduced the sediment entering the bay considerably. An earlier dam was overtopped in 1916, increasing the floodwaters coming down Mission Valley at the time. The Mission Bay and San Diego River jetties were built in 1948, at a time when the shore of the bay was subject to alternating periods of recession and advance. By February 1951, the river levees had been connected to the jetties. All tidal flow was confined to a new channel. Since the river discharges only during flooding, the middle channel was soon completely filled. The channels were finished by 1955, after various difficulties were overcome and the jetties were considerably lengthened so that shallow bars would not form in the entrance. Extensive dredging was done in Mission Bay to make the channel deep enough for a yacht basin, and other areas were developed to accommodate swimming and other recreational activities (Figures 99a, 99b).

5.332 Coastal Changes. There is no cliff contribution within the Mission Beach Littoral Cell as no cliffs or bluffs exist within this coastal segment. For shoreline changes, i.e. fluctuations in the mean high water and lower low water (U.S. Army Corps of Engineers Beach Erosion Report Appendix IV, 1960).

Ocean Beach to Point Loma

5.333 Morphology. The community of Ocean Beach extends south into Sunset Cliffs, a residential area in the City of San Diego, at the north end of Point Loma. The northern part of Ocean Beach is built on a remnant of an old delta deposit of the San Diego River (Figure 102). Historically, the beach in this area was subject to periods of accretion following floods. Since the building of the jetties, the beach has had to be maintained by the spoil from dredging.

5.334 South of Ocean Beach, the coast rises, and consists of Cretaceous and Pleistocene sedimentary strata, which form the scenic Sunset Cliffs area of Point Loma. The point itself rises to a height of about 400 feet, with steep sides at the southern end. It is similar in appearance to Soledad Mountain to the north.

5.335 Coastal Changes. Erosion of the cliff along this coastal segment, for the period studied, has contributed a negligible amount of sediment to the beaches.

5.336 It was noted by Kennedy (1973) that sea cliff retreat along the resistant Cretaceous cliffs at Sunset Cliffs amounted to only three feet between 1898 and 1973, or when averaged only about two inches per year. An exception was pointed out; namely, where a cave roof collapsed, local retreat could be much greater. This episodic, highly site-specific rapid retreat has endangered the road at several locations along the cliff.

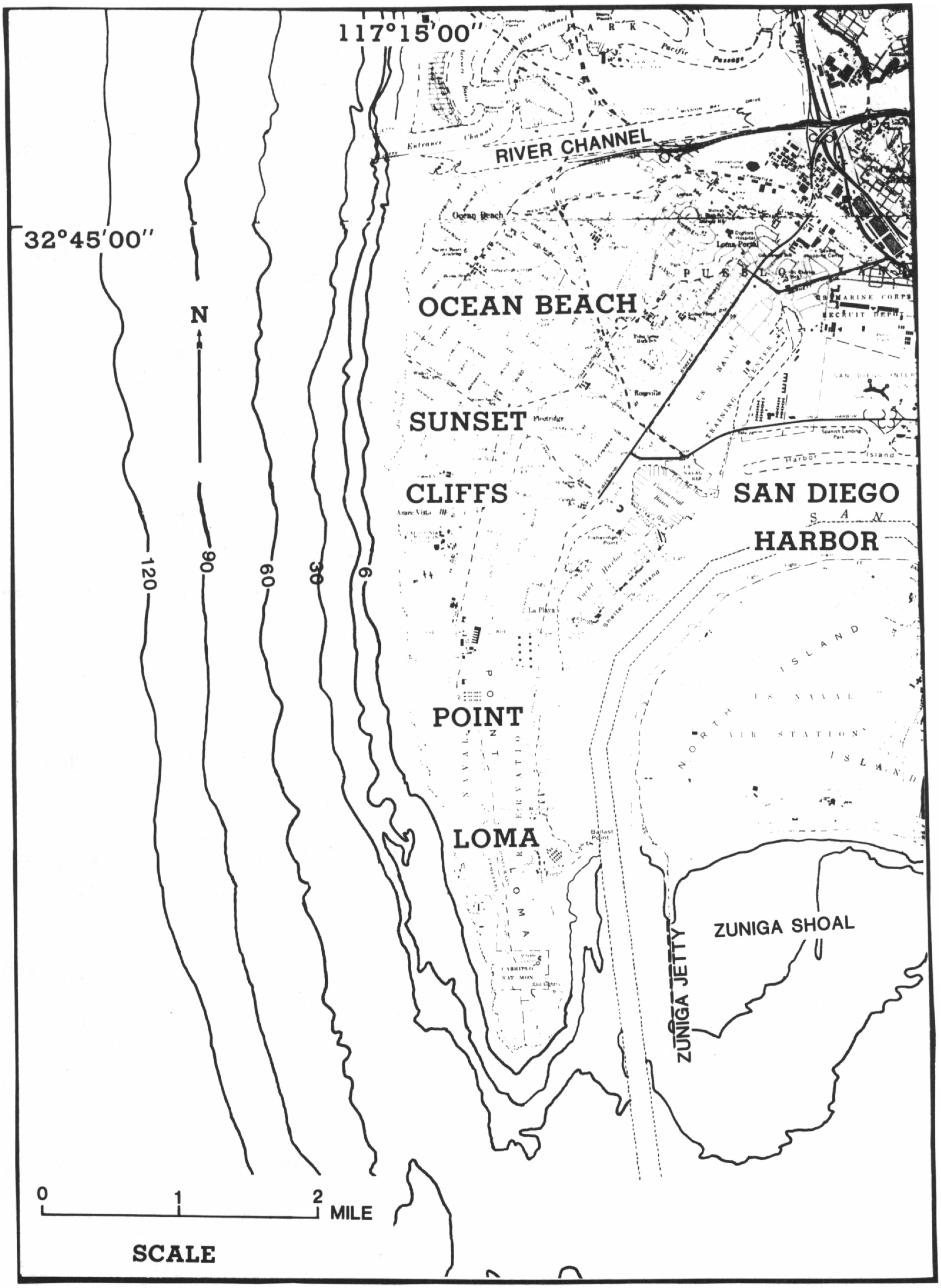


Figure 102. Location map of Ocean Beach, Sunset Cliffs, and Point Loma. Note: Bathymetric contours in feet (from Kuhn and Shepard, 1984).

5.337 Examination of the early U.S. Coast and Geodetic Survey topographic field sheets of 1889 were made and the surveys were compared with the U.S. Geological Survey of 1948. Little change is evident along the base of cliff or slope toe when using the 1:24,000 scale maps of the U.S. Geological Survey.

Silver Strand Littoral Cell

5.338 The Silver Strand Littoral Cell extends from the entrance of San Diego Bay southward to beyond the international border (Figure 103), a distance of approximately 13 miles along the shoreline. This littoral cell has its own source, northward transport path and sink. The principal source of sediment for this cell is the Tijuana River. The sink is located on and seaward of Zuniga Shoal (Inman, 1976).

5.339 Morphology. Coronado was a combination of two islands with a swampy area between them. The swamp is now entirely filled with sediment brought in by the Navy when the military base was established to the south. There is a long spit that extends from the embayment of the Sweetwater River. An extensive delta has built up much of the land at the mouth of the Tijuana River. The delta extends as far south as the Mexican border (Kuhn and Shepard, 1984).

Zuniga Jetty and the Building of the Hotel del Coronado

5.340 In 1888, the Hotel Del Coronado was built at the northern end of Coronado on a poorly-developed sand spit (Figure 104). In 1893, construction began on a 7,500-foot-long jetty on Zuniga Shoal, intended to stabilize the entrance to San Diego Harbor. This rubble structure, located west of the hotel, was completed in 1904. Erosion problems developed on the spit immediately following construction of the hotel, and a small stone breakwater was built to the southeast, in 1897, to offer protection from wave erosion. It was damaged and repaired at a later date.

5.341 Erosion of the beach occurred just west of Spanish Bight in 1900, following extension of the Zuniga Jetty. Railroad tracks northwest of the jetty had to be relocated in 1901. Erosion continued during the next extension of the jetty in 1903-1904, which took it farther east of Spanish Bight. Severe storms beginning in January 1905 caused erosion both north and south of the Hotel Del Coronado (Figure 105a, 105b). On January 4 and again on February 18, waves focused on the hotel area, necessitating the installation of 30,000 two-hundred-pound sandbags. February and March storms continued to cause serious wave erosion, and a total of 110 feet of land was removed by the waves along Ocean Boulevard (Figure 106); the houses left undamaged were subsequently relocated to downtown San Diego. Between 1905 and 1908, a 5200-foot-long seawall was built from the hotel west along Ocean Boulevard.

5.342 A massive rock seawall was constructed in 1905, the eroded area was backfilled and the street was restored.

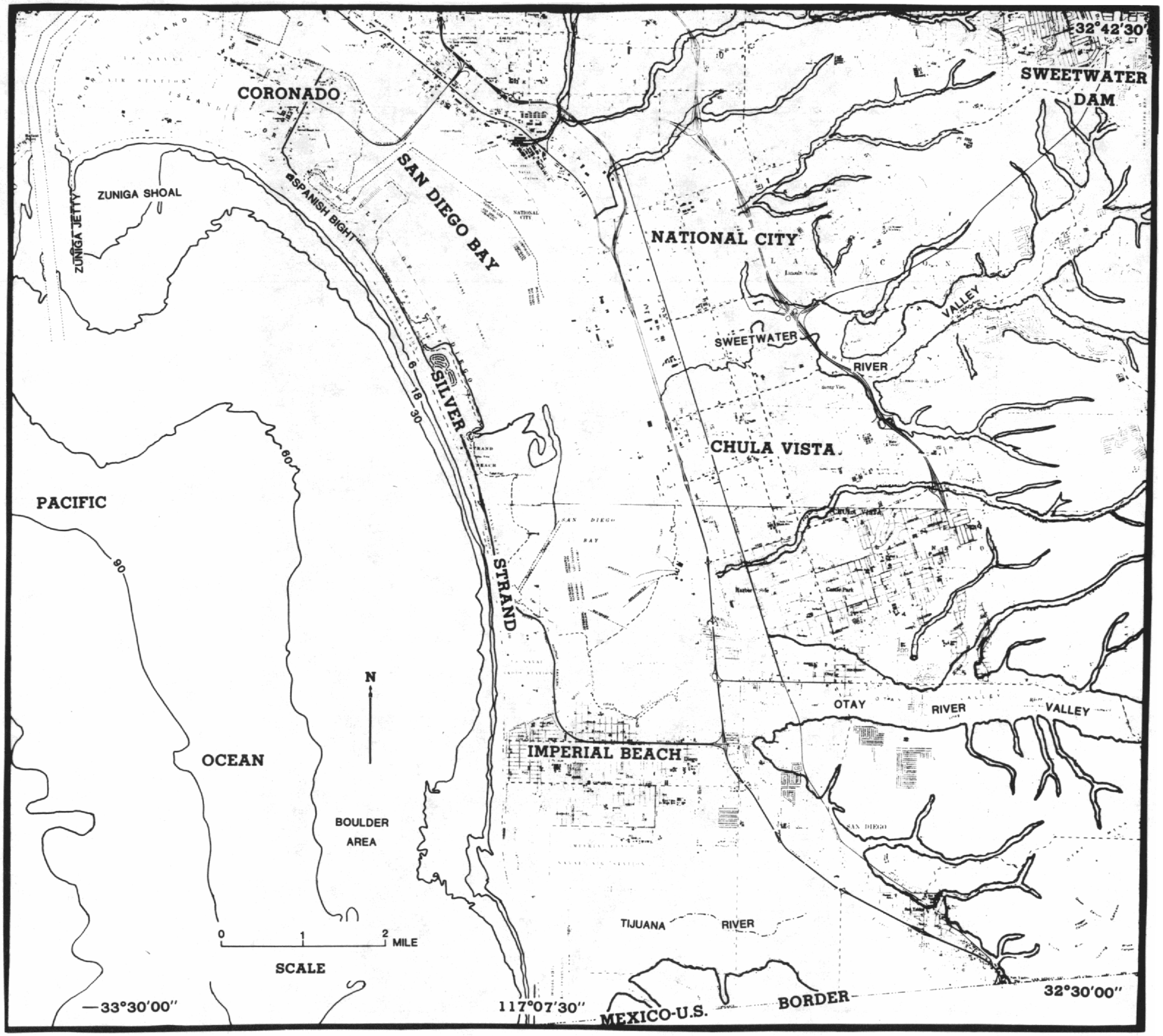


Figure 103. Location map of Coronado and Imperial Beach southward to the Mexican Border. Note: Bathymetric contours in feet (from Kuhn and Shepard, 1984).

Figure 104. View looking south at the Coronado sand spit in 1898 (photograph from U.S. Grant IV photographic collection).

Figure 105a. View looking south along the beach cliff toward the Hotel Del Coronado in January 1905 (photograph from F. P. Shepard Collection).

Figure 105b. March 1905 view of the same site as that in 105a. Note the severe erosion of the beach cliff and that approximately 30,000 two-hundred pound sandbags had been placed north and south of the hotel, to save it from destruction by the waves (photograph from F. P. Shepard Collection).

Figure 106. View looking north from the Hotel Del Coronado in March 1905. The photograph was taken following severe sea storms which eroded approximately 110 feet of beach and cliff sediment to the north of the hotel (photograph courtesy of Center for Coastal Studies Scripps Institution of Oceanography).

5.343 In 1912, the seawall had to be reconstructed in much larger proportions as a result of more severe storms.

5.344 As late as 1938, waves broke over the seawall during large storms.

5.345 The City of San Diego Planning Department (1969) indicated that:

> "It is important to note that the beach area seaward of this wall remained denuded of sand from the time of the 1905 storms until 1940 when over two million cubic yards of dredge spoil from San Diego Bay were deposited along the beach at North Island. Even this had little effect on Coronado beaches".

Silver Strand Beach Nourishment

5.346 More than two million cubic yards of sedimentary fill material was deposited from Zuniga jetty south to the Hotel Del Coronado about 1941 (Shaw, 1980). Subsequent surveys indicated that the shoreline temporarily advanced more than 800 feet in that area. The fill material eventually migrated with widening the beach south of Zuniga jetty.

5.347 Between 1942 and 1946 as much as 25 million cubic yards was deposited on the beach from the Hotel Del Coronado south widening the beach a maximum of almost a thousand feet (Shaw, 1980). The beaches retreated by approximately 450 feet by 1958.

5.348 Coastal Changes. There are no cliffs within the Silver Strand Littoral Cell that contribute sediment to the beaches north of the mouth of the Tijuana River.

5.349 Erosion at Imperial Beach has been an increasing problem during drought periods since 1953 and preceding the recent floods of 1978 to 1980 (for a detailed discussion of Erosion at Imperial Beach for this period of time see Kuhn and others (1987) in the U.S. Army Corps of Engineers Report CCSTWS 87-2).

Summary of Cliff and Bluff Erosion: 1887-1947

5.350 Between 1887 and 1947, certain distinct wet years have accelerated subaerial erosion at site specific areas along the coastal cliffs and bluffs from Dana Point to the Mexico border.

5.351 During the wet years of 1889-90, 1890-91, 1902-03, 1904-05, 1915-16, 1921-22, 1926-27, 1936-37, 1937-38, 1939-40 and 1940-41, heavy rainfall (Figure 107) occurred with associated cliff face retreat, lateral and headward cutting of canyons, erosion of coastal terrace surfaces, bluff face gullying and mass wasting of cliffs and bluff along San Onofre State Park and Camp Pendleton (Figure 50).

5.352 Of the forementioned storm years, most of the coastal cliff and bluff erosion probably was related to storms in 1889-90, 1890-91, 1915-16, 1921-22 and 1940-41. Due to the intense and temporally concentrated rainfall associated with these storm years as well as the installation of storm drains associated with the construction of State Highways 1 and 101 from 1912 to 1922, volumetrically significant quantities of sediment were delivered to the beach areas along San Onofre State Park and Camp Pendleton during this period.

5.353 It should be noted that erosion rates and sediment yield probably were much greater during the extremely stormy years of 1861-62 and 1883-84 than those for the years discussed in paragraph 5.352. Unfortunately the effects of these two events on the southern Orange County and San Diego County coastlines cannot be documented at this time, because the baseline topographic surveys of the U.S. Coast and Geodetic Survey were not initiated until 1885 and those of the U.S. Geological Survey until 1891.

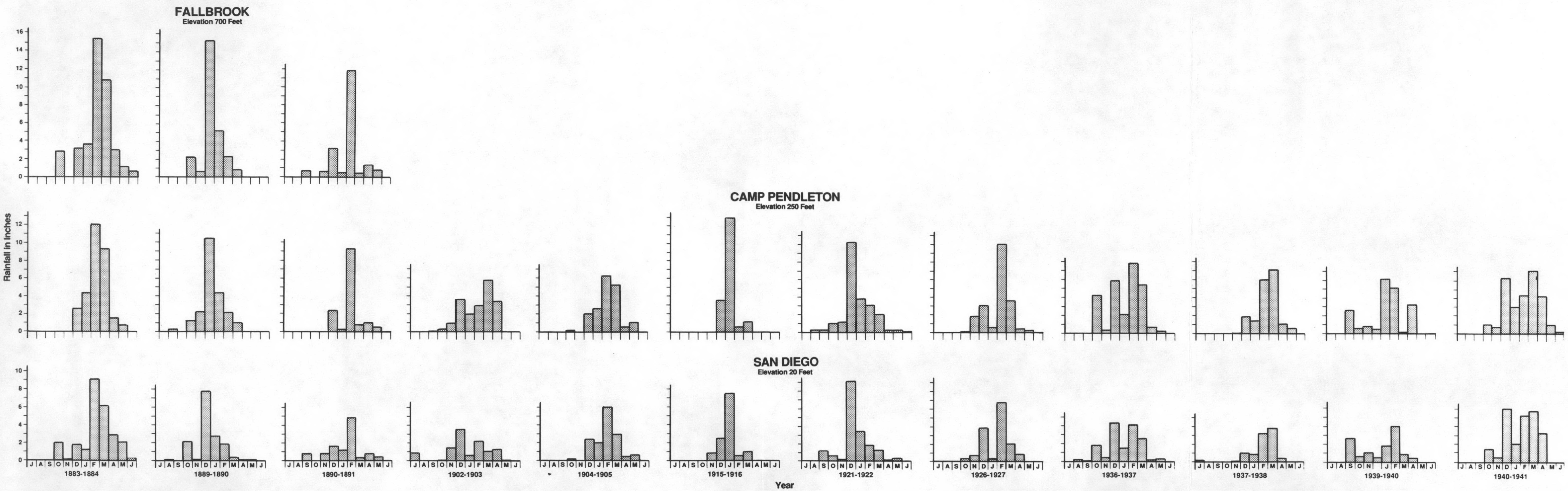


Figure 107. Histograms of monthly rainfalls for the most significant storm/flood years between 1884 and 1947. For the wet years of 1883-84, 1889-90, and 1890-91, the rainfalls for City of San Diego, Camp Pendleton and Fallbrook are shown. For the water years 1902-03, 1904-05, 1915-16, 1921-22, 1926-27, 1936-37, 1937-38, 1939-40, and 1940-41, rainfalls at the City of San Diego and Camp Pendleton are shown. Note: "Normal rainfall" for the City of San Diego between 1850 and 1890 is approximately 10 inches per year (County of San Diego).

6. COASTAL TERRACES

Introduction

6.1 Perhaps the best-known geomorphic feature of the southern California coast is its series of raised marine terraces which rise in steps from the beach up the slopes of adjacent mountains (Emery, 1960).

6.2 Between Dana Point and the Mexican border Figure 1, marine terraces and beach-ridges (Figure 108) record a series of Quaternary sea-level high-stands superimposed on tectonically rising segments of the California coast (Lajoie et al., 1979). These terraces are extremely important to study as they are fronted by sea cliffs exposed to both marine and subaerial processes.

6.3 Erosion of the coastal terrace which extends for more than 14 miles along the coast at San Onofre State park and Camp Pendleton has contributed significant quantities of sediment to local beaches during the stormy-wet years between 1887 and 1987 (Kuhn and others, 1987). In recent years since 1968, erosion rates have greatly accelerated as a result of works by man (Kuhn and others; 1987, Kuhn and Shepard, 1984).

Marine Terrace Terrain: A Definition

6.4 In this report the term <u>marine terrace terrain</u> as defined by Cleveland (1975) is used to describe a series of emerged wave-cut platforms that parallel the coast and are generally covered with surficial deposits. The term <u>terrace</u> is used in a very general way to indicate an individual platform in a terrace terrain. The <u>back</u> of the terrace is its landward limit and the <u>edge</u> is its present seaward limit. The <u>landward limit</u> is most often marked by an abrupt change in slope, which ordinarily is a former sea cliff.

6.5 As noted by Cleveland (1975), it is not always possible to determine whether tectonic uplift or a eustatic drop in sea level has been the primary cause for the present position of the terraces. Thus, the terraces are referred to as <u>emerged</u> terraces, with no distinct connotation implied as to whether they are uplifted or perched features.

6.6 Cleveland (1975) also indicated that the terrace platform is generally veneered by relatively thin, poorly-consolidated and poorly-sorted marine deposits overlain by non-marine alluvial sediments derived from streams that debouche onto the marine terrace deposits.

Marine Terrace Terrain: San Onofre State Park and Camp Pendleton

6.7 A number of marine terraces consisting of wave-cut benches, partly mantled by marine and non-marine deposits, are found on the seaward edge of the San Onofre Mountains (Ehlig, 1979).

6.8 The lowest terrace forms a coastal bench and is essentially intact. Late Quaternary pediment fan and mudflow sedments, 30 to 90 feet thick overlie the marine wave-cut platform and terrace deposits. The marine deposits have been dated by amino-acid and uranium-series assay of molluscs and corals (Ku and Kern, 1974; Wehmiller and others, 1977) at approximately 125,000 years B.P. (Before Present) (Schlemon, 1979).

6.9 Maximum rates of uplift for this section of coast is tentatively reported to be approximately 0.3 meters per thousand years (Lajoie and others, 1979).

Terrace Drainage Evolution

6.10 A model of drainage evolution which applies to a shoreline of emergence was proposed by Putnam (1937) and more recently by Cleveland (1975). This model of terrace drainage evolution may be applied to the San Onofre State Park and Camp Pendleton areas.

6.11 The evolution of the drainage pattern as described by Cleveland, 1975) appears to occur in the following stages:

Stage 1. In the initial stage of evolution, an adjacent highland area is eroded by marine processes which leads to the development of a sea cliff (Figure 108A). The highland area is drained by both local streams, the flow from relatively small drainages nearby, and by streams whose flow is derived from inland drainage basins.

6.12 Stage 2. As sea level drops relative to the land, base level is lowered, thus exposing the nearshore portion of the former sea floor. Alluvial fans cover the terrace deposits when the streams carrying capacities are diminished upon encountering the shallow gradient of the surface of the terrace. Stream flow is dissipated by numerous distributaries on the surface of the fan and by percolation into the alluvial deposits. Drainage patterns change as a result of gully development back from the modern sea cliff (Figure 108B). Gullies subsequently enlarge and erode headward toward the main sources of flow along the periphery of the alluvial fan or incipient channels which may have formed on the terrace surface. A gully may eventually capture a distributory channel and create a direct conduit across the terrace from the inland segment of the stream course to the ocean.

6.13 Stage 3. In the third stage the full flow of the main stream is focused and channeled into a single narrow stream course as a result of all the other distributaries being bypassed. Erosional energy is concentrated in two directions 1) lateral cutting and/or undercutting of the slopes and 2) downcutting of the stream bed (Figure 108c). Lateral erosion with an associated increase in steepness of the slopes, especially near the back of the terrace, is exacerbated by the narrowness of the stream course. Landslide movement is most common in this stage as lateral support is being removed and slopes are rapidly becoming higher and steeper.

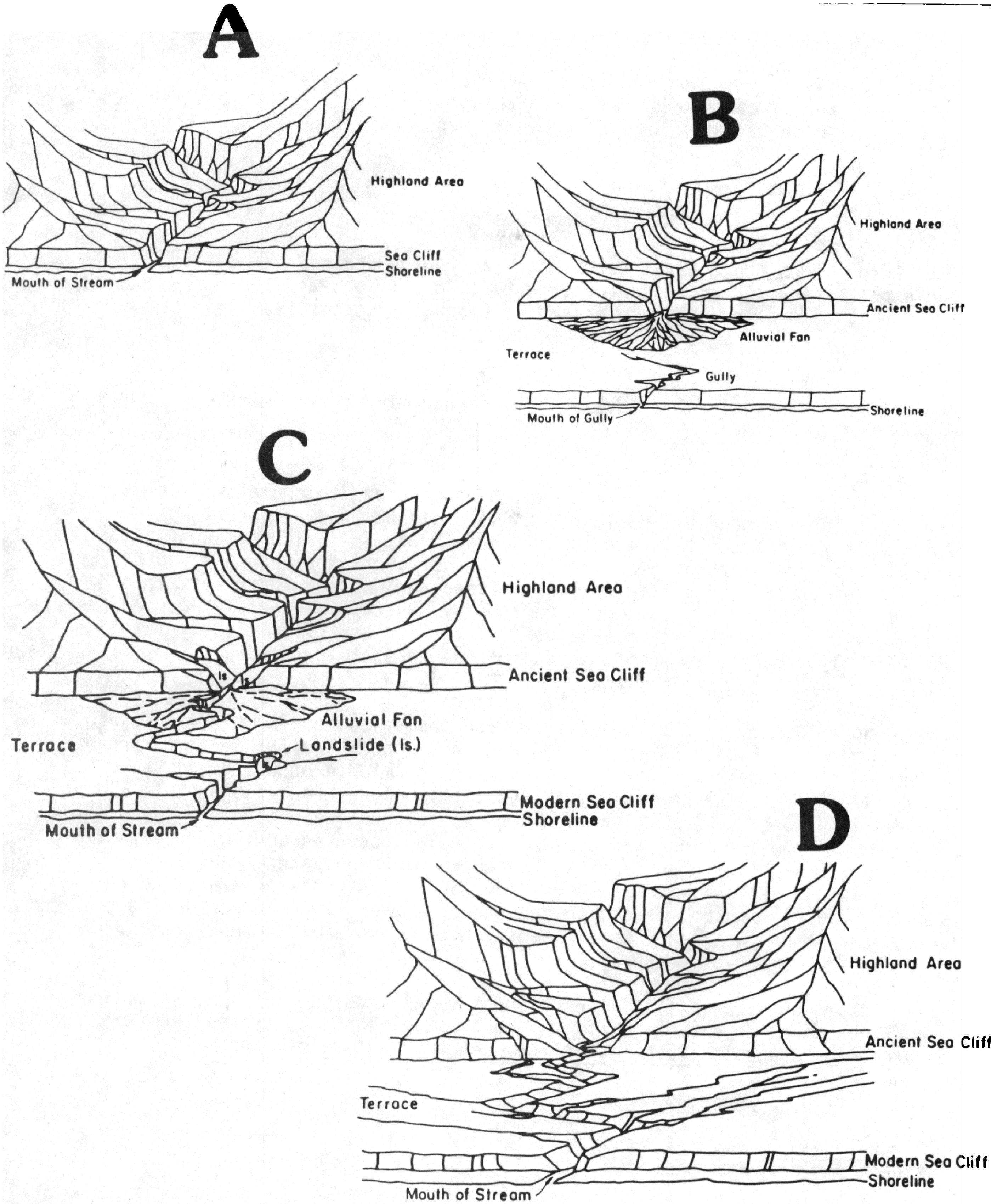


Figure 108. Terrace drainage evolution (from Cleveland, 1975).

6.14 Stage 4. Equlibrium and landslide activity is restored and both segments of the stream course develop a common long profile when the stream channel on the terrace has been enlarged to accomodate normal flow (Figure 108d).

Coastal Terrace Erosion Processes

6.15 Erosion of the coastal terrace at San Onofre State Park and Camp Pendleton is seen to occur under both natural conditions and, in recent years, as a result of man-induced accelerated erosional processes (Kuhn and others, 1987).

6.16 Subaerial erosional processes have been dominant over marine erosion between 1887 and 1987.

6.17 Subaerial erosional processes which occur along this coastal segment are: 1) rainfall induced landslides, 2) lateral and headward erosion along canyons cut ino the coastal terrace as a result of man's alteration of existing drainage patterns by diverting surface runoff from the San Onofre Mountains directly east of the coastal terrace and focused the runoff into storm drain culverts located under the freeway, which subsequently incised the coastal terrace; 3) gullying of the coastal terrace and cliff face by rain wash, and 4) surface erosion of the top of the coastal terrace.

6.18 Landslides along this coastal terrace appear to be directly related to periods of intense sediment saturation and large storm swell. Several large landslides occurred during wet years. During the middle of a wet and storm period (1941), a landslide measuring 1700 feet in length and 350 feet in width occurred in June (Figure 51). More recently, a landslide measuring approximately 700 feet long and 300-320 feet wide occurred during January 1978 as a result of a rise in pore-pressure induced by groundwater (Kuhn and Shepard, 1984). Also as indicated by Cleveland (1975), the origin of certain landslides appears to be related to sequences of events that occur during the development of the drainage of different groups of streams on the terrace.

6.19 Schumm and others (1987) described several erosion processes which are commonly observed on natural surfaces and are applicable to terrace erosion. The processes are rainsplash, sheetflow, concentrated runoff and mass movement.

6.20 Rainsplash detaches soil particles and sand grains from the terrace surface and transports them.

6.21 Sheetflow occurs when heavy rainfall saturates the soil then runoff collects into more or less distinct flow lines. Schumm and others (1987) notes that under close examination the water flowing in thin sheets and at low velocities roll sand and soil grains toward the nearest channel on a surface.

6.22 Concentrated runoff. As runoff is concentrated into distinct flow lines, its erosive force is enhanced (Schumm and others, 1987), and when base level is lowered, nickpoints move rapidly upslope along flow lines, cutting channels.

6.23 Mass movement. Schumm and others (1987) notes that incised channels tend to cut laterally and meander. Undercutting of the banks occurs, leading to bank caving and subsequent widening of the main valleys. Once mass movement widens the valley sufficiently to provide the channels space to meander freely, then surface erosion continues to reduce the slope angles of the steep valley sides.

6.24 These natural erosion processes, when combined with alteration of drainage patterns by man, can greatly accelerate erosion rates.

6.25 Since 1885, normal erosion along drainage avenues at San Onofre State Park and Camp Pendleton have been drastically altered by man. Railroad trestles were built across canyons in 1885, but apparently they did not alter the drainage pattern. The construction of Highway 101, beginning in 1912 through 1918, first altered the natural drainage patterns with the installation of culverts under the highway to channel surface runoff. In the wet years that followed, gully erosion was accelerated where the culverts concentrated water flow.

6.26 Dead Dog Canyon, south of Horno Canyon on Camp Pendleton, was seen as just a Notch on the cliff top in 1889 (Figure 52). Between 1889 and 1932 it eroded landward very little (Figure 53); between 1932 and 1977, it enlarged 560 feet headward; in 1978, the canyon eroded another 100 feet (Figure 54b); and another 100 feet eroded in February 1980 (Figure 54c).

6.27 In 1889, at the present location of the San Onofre Nuclear Power Plant, barranca and gullying was apparent (Figure 56). Photographs taken in 1932 (Figure 57), 1941 (Figure 58), 1953 (Figure 59), 1964 (Figure 60), and 1972 (Figures 61, 62) clearly illustrate marked headward erosion across the coastal terrace.

6.28 Gullies cut into the coastal terrace and cliff face contribute significant amounts of coarse-grained sediment by increasing the surface area of cliff material exposed to erosion (Figure 55).

7. ESTIMATES OF EROSIONAL RATES AND SEDIMENT YIELD FOR SEA CLIFFS AND COASTAL TERRACES

Introduction

7.1 Rates of erosion and associated sediment yields can be calculated by comparing the topography for the same sections of coastline that were surveyed at different periods of time. Inputting into a computer each contour on the topographic map as a series of (X,Y,Z) coordinates, and then gridding the irregularly-spaced data into an evenly-spaced grid or matrix permit the computation of a two-dimensional data set representing the elevation at the time the map was surveyed. Subtraction of the two matrices, each representing elevation over the same area, but at different periods of time, results in a matrix representing elevation gained or lost over time. Since the size of each position or cell in the matrix is known, the volume gained or lost can be calculated for the entire region, or for subregions of the matrix. This can be used to determine an overall rate of erosion or aggradation, as well as to estimate sediment yield for the time interval between the two surveys.

7.2 Three topographic maps from 1889 and three maps from 1968 were used for this study. These maps are:

U.S.C.G.S., 1889, Map #T-2014, 1:10,000
U.S.C.G.S., 1889, Map #T-2015, 1:10,000
U.S.C.G.S., 1889, Map #T-2016, 1:10,000

San Onofre Bluff, Calif., 7.5-minute series (topogrpahic, 1968
Las Pulgas Canyon, Calif., 7.5-minute series (topographic), 1968
Del Mar, Calif., 7.5-minute series (topographic), 1967

The 7.5-minute topographic series maps have a scale of 1:24,000.

7.3 From each map, all elevation contours along the coastline, the cliffs, and the terraces were entered into the computer as a series of (X,Y,Z) coordinates using a digitizing tablet. Elevation contours within the foothills were not included in this study. Matrices representing elevation were created for the San Onofre, Camp Pendleton, and Torrey Pines regions for each of the two time periods, 1889 and 1968. The region where the contours were digitized varied from 500 yards from the shore in the northern part of the San Onofre area, to 750 yards inland in the southern part of San Onofre. Contours were collected from the shore to 750 yards inland for Camp Pendleton, and from the shore to 1000 yards inland for Torrey Pines. The (X,Y,Z) data were processed into two-dimensional matrices using a cubic spline gridding method. Matrices from the two time periods for each region were then subtracted resulting in a matrix of change in elevation for each region.

Digitizing

7.4 Elevation contours on each topographic map were converted into (X,Y,Z) coordinates using a digitizing tablet connected to a host computer. The digitizing tablet that was used has a resolution of 1000 lines per inch. After securing the map onto the tablet, the analyst digitized points such as bench marks and other features common to the 1889 and 1968 maps so that the individual data sets could be correlated with each other. To digitize a feature, the analyst place the digitizing puck over the feature and press the puck button. This caused the digitizer to transmit the tablet's (X,Y) coordinate to a program running on the host computer where the data was processed and stored.

7.5 All contours were digitized as a set of continuous vectors. For each contour, the analyst would first enter into the computer program the elevation (Z) of the contour that was to be digitized (i.e., Z=80 feet). The analyst would then place the puck on the contour, and enter points from one end of the contour to the other. Points would be entered relatively far apart along straight sections of the contour, and close together along curved sections. The resulting digitized vectors could be open or closed. The analyst also would enter points and vectors to show topography not represented by contours printed on the map, such as crests of hills.

7.6 After the topographic maps were digitized, the data sets from each time period were converted into a common coordinate system. This included transforming the data from the 1968 maps (1:24,000) to the same scale as the 1889 maps (1:10,000), as well as adjusting for any lateral and rotational differences of the maps as they were placed on the digitizing tablet. Figures 109, 110 and 111 show each data point as digitized for the three regions, San Onofre, Camp Pendleton, and Torrey Pines in 1889, whereas figures 112, 113 and 114 show the data as digitized for the same regions in 1968.

Gridding

7.7 To compare elevation from one time period with elevation from another, each of the 6 digitized data sets (3 regions from 1889, 3 regions from 1968) must be converted from a set of irregularly-spaced points into an evenly-spaced grid or matrix of cells. The value of each cell in the matrix can be thought of as representing the average elevation over that cell. It was decided that the matrices would be 1000 columns by 500 rows, with each cell in the matrix being 25 feet by 25 feet. Most of the matrix would have the value zero where no data was collected, such as over the ocean and over the mountains.

7.8 The data was collected along known elevation (Z) at irregularly-spaced (X,Y) values. The purpose of gridding is to calculated the elevation (Z) at regularly spaced columns (X) and rows (Y). Since each elevation contour was digitized as a vector or line segment, (Z) is known for every possible point (X,Y) along that vector. It is possible to calculate the intersection (Y) of each contour (Z) with each column (X) of the matrix. Figures 115-120 show the data points for each region and time period after interpolating in this manner.

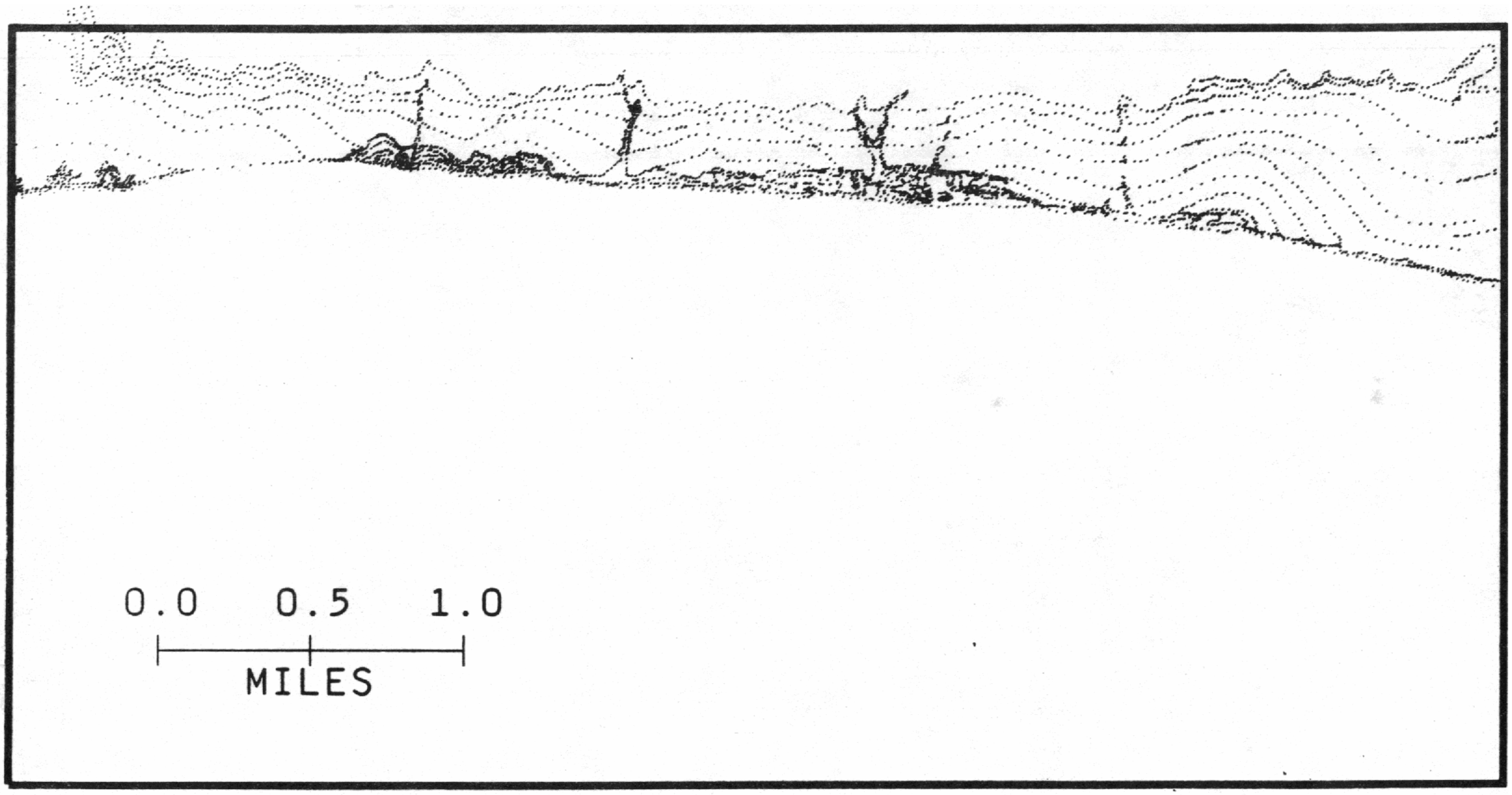


Figure 109. Digitized data points for the San Onofre region in 1889. Area digitized extends along longitude 117°30'00" from latitude 33° 22'30" downcoast to 33°19'00" (Figure 50).

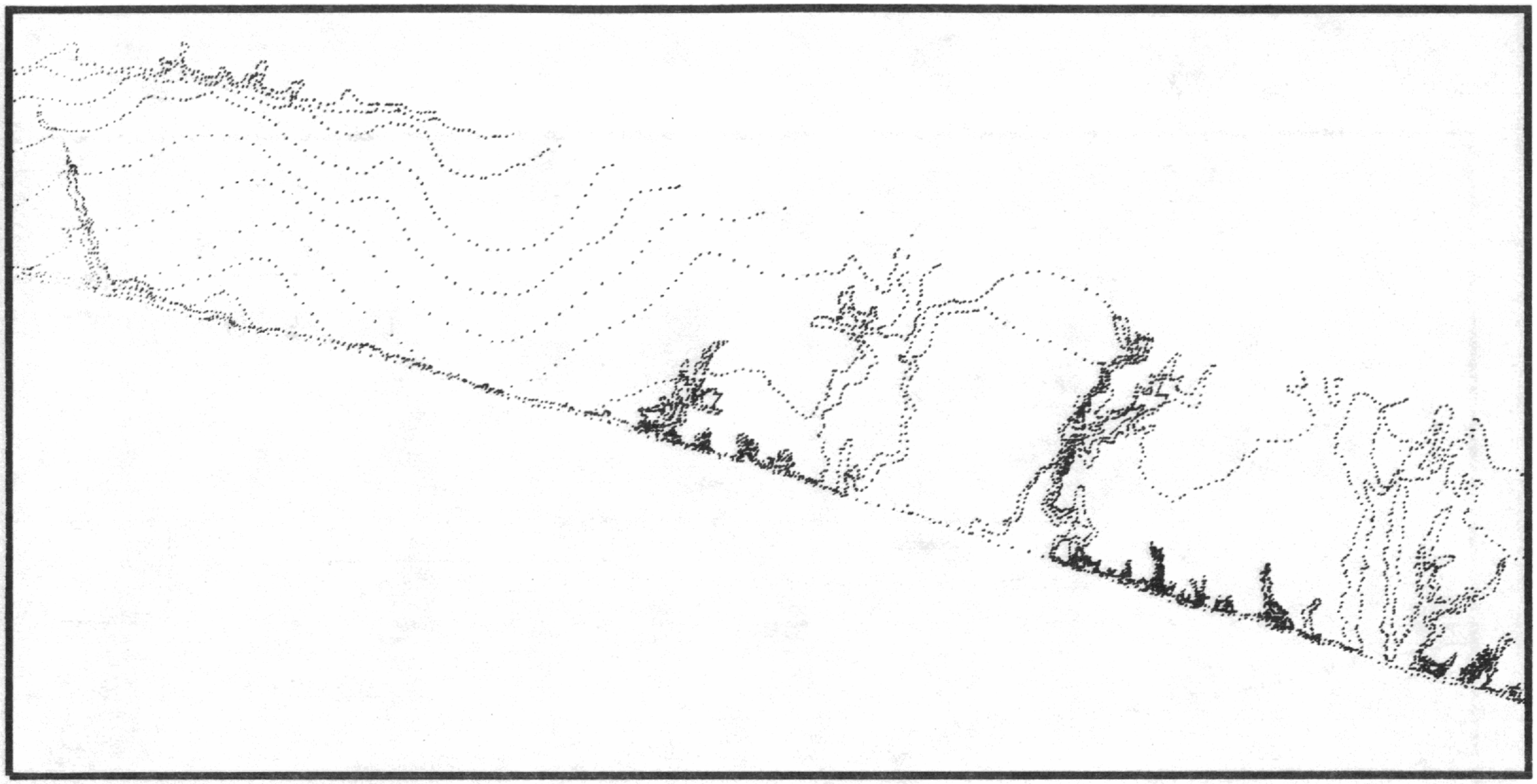


Figure 110. Digitized data points for the Camp Pendleton region 1889. Area digitized extends from longitudes 117°30'00" to 117°25'30" and from latitude 33°19'00" downcoast to 33°15'00" (Figure 50).

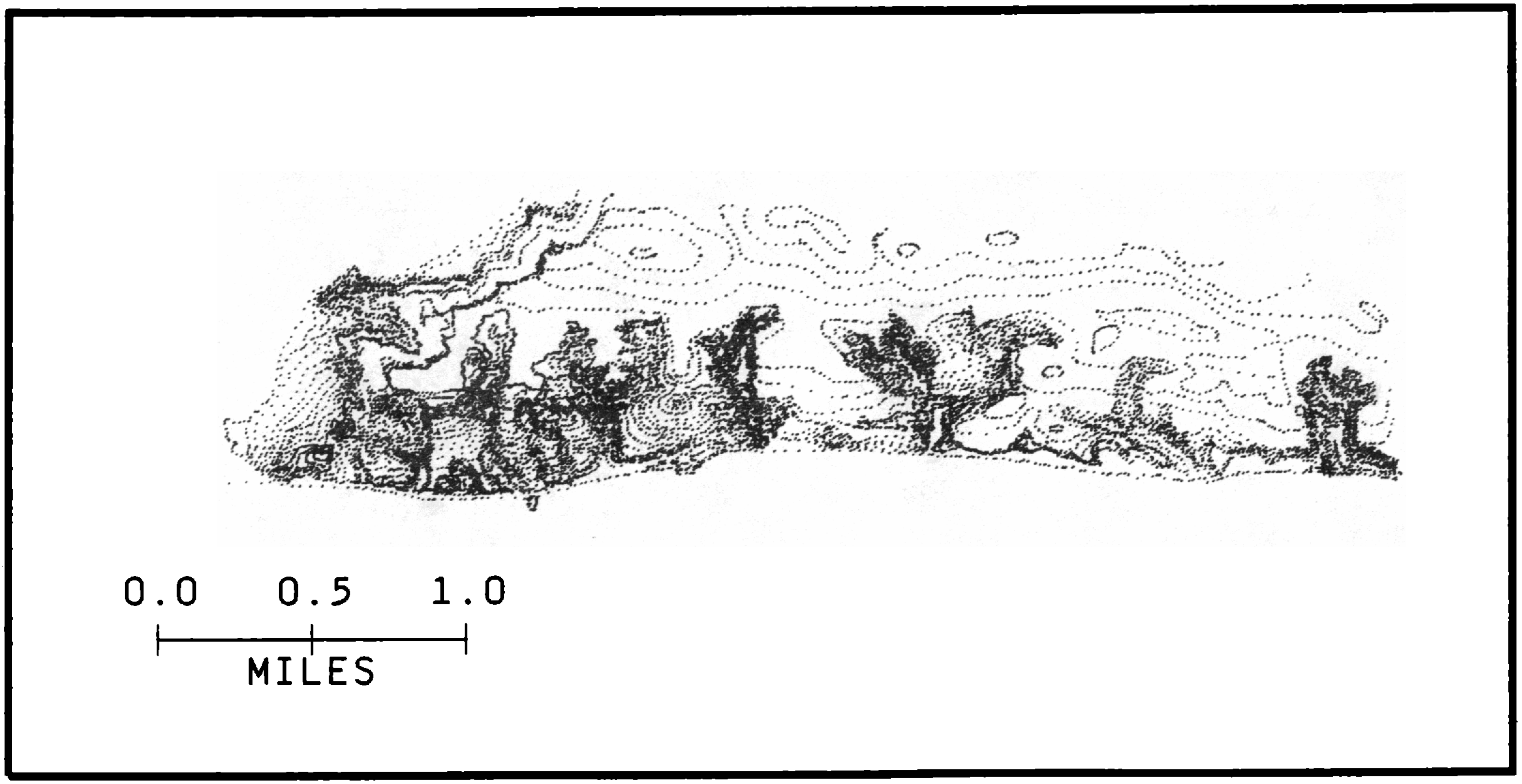


Figure 111. Digitized data points for the Torrey Pines region in 1889. Area digitized extends along longitude 117°15'00" from latitude 32°56'00" downcoast to 32°52'30" (Figure 88).

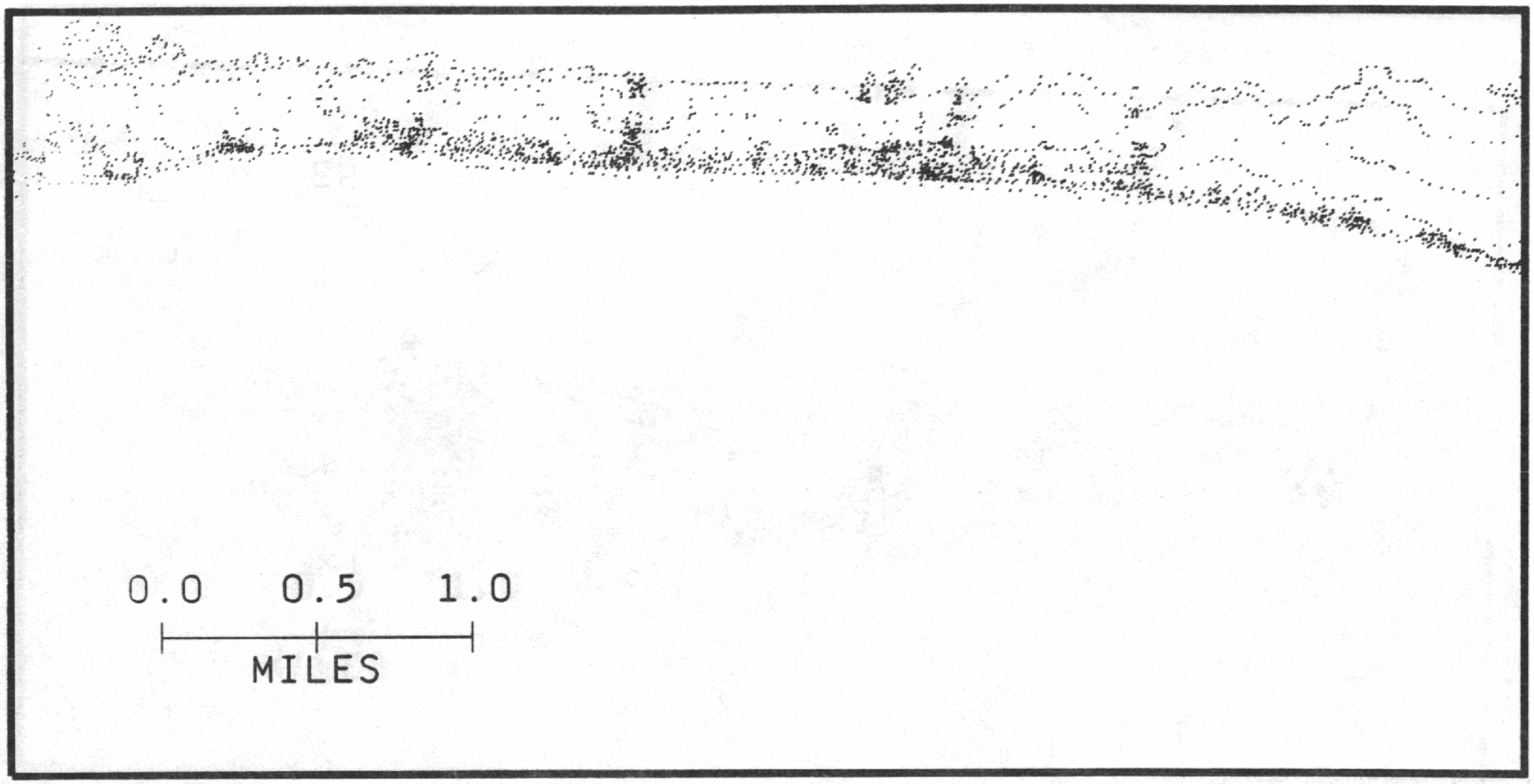


Figure 112. Digitized data points for the San Onofre region in 1968.

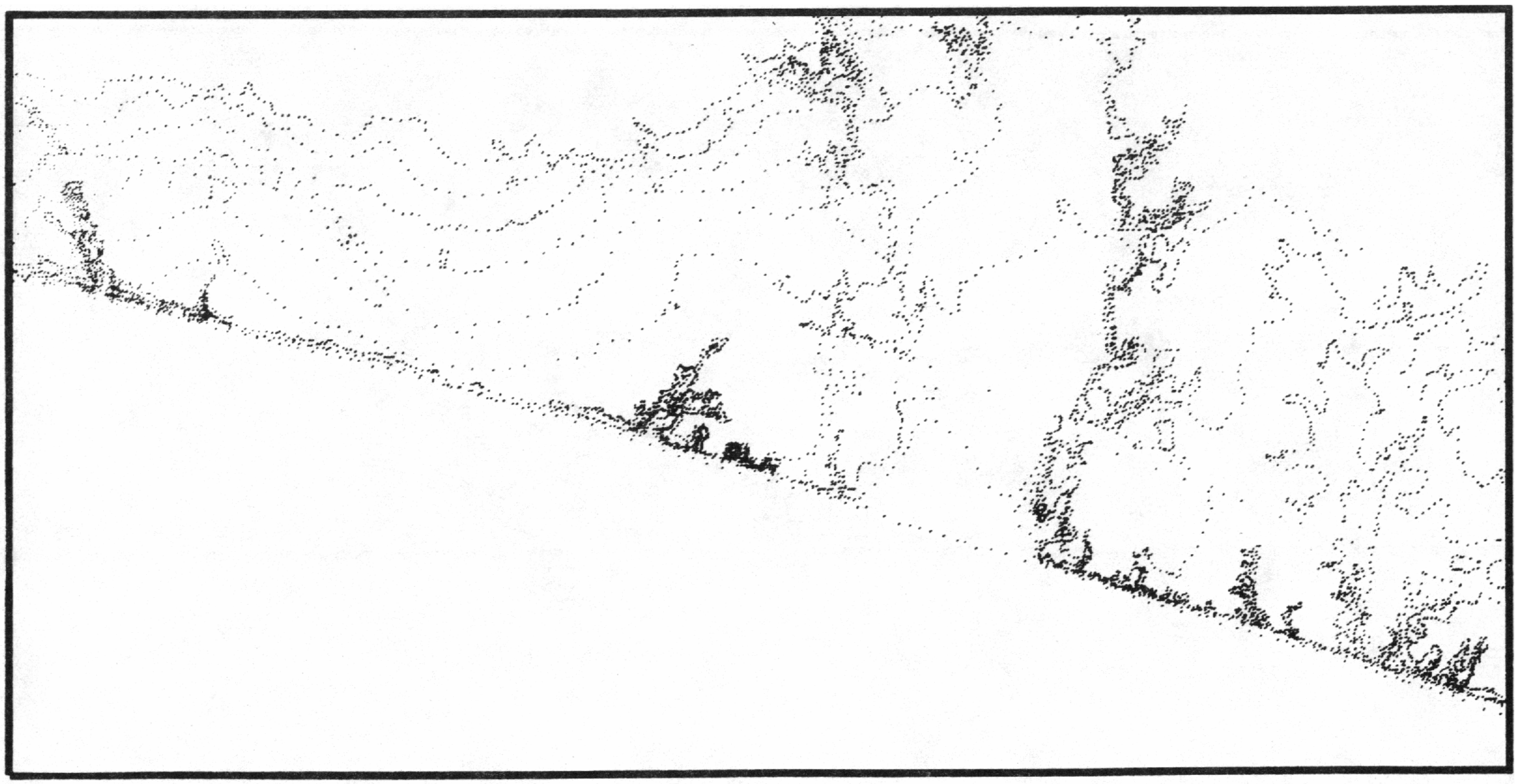


Figure 113. Digitized data points for the Camp Pendleton region in 1968.

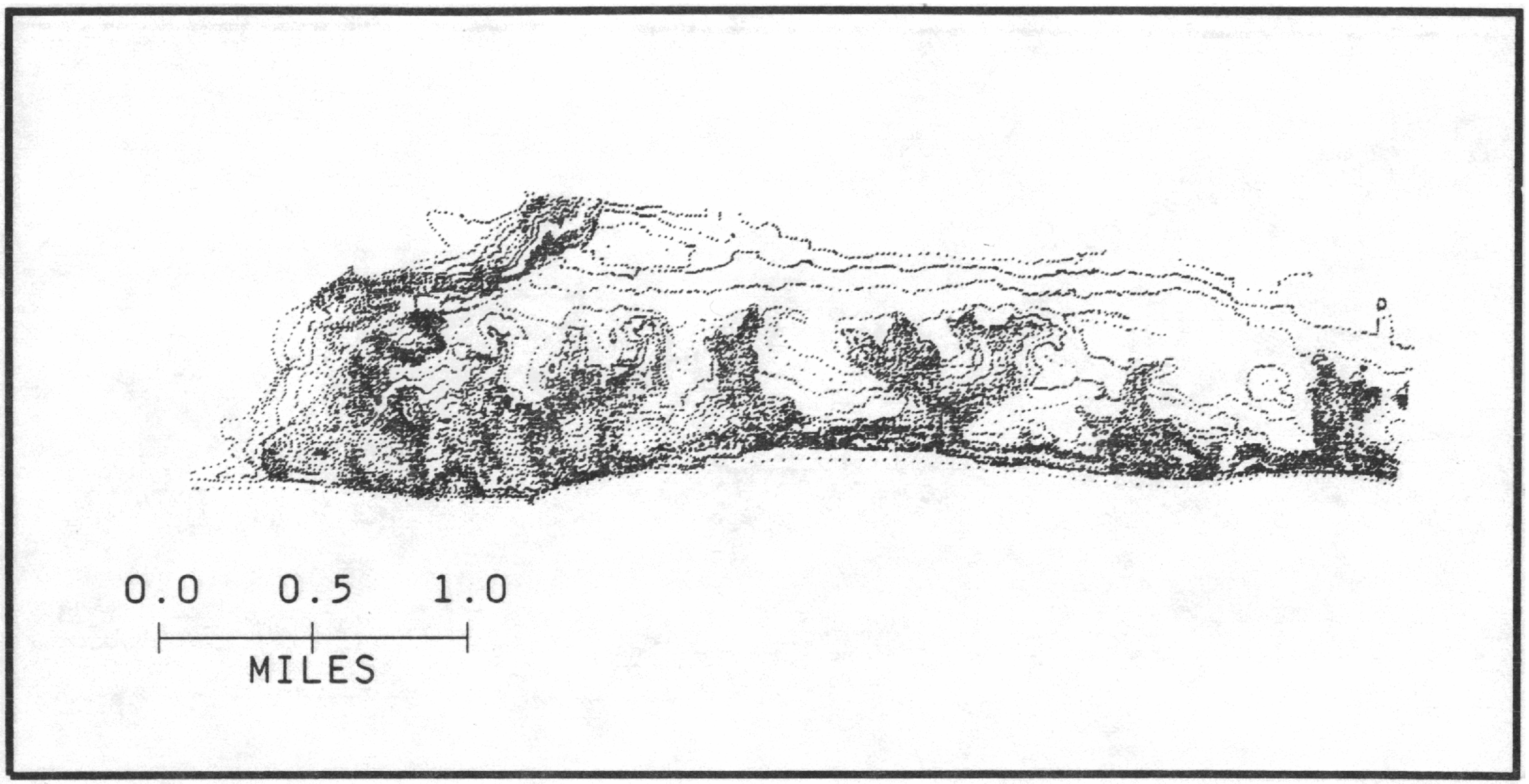


Figure 114. Digitized data points for the Torrey Pines region in 1968.

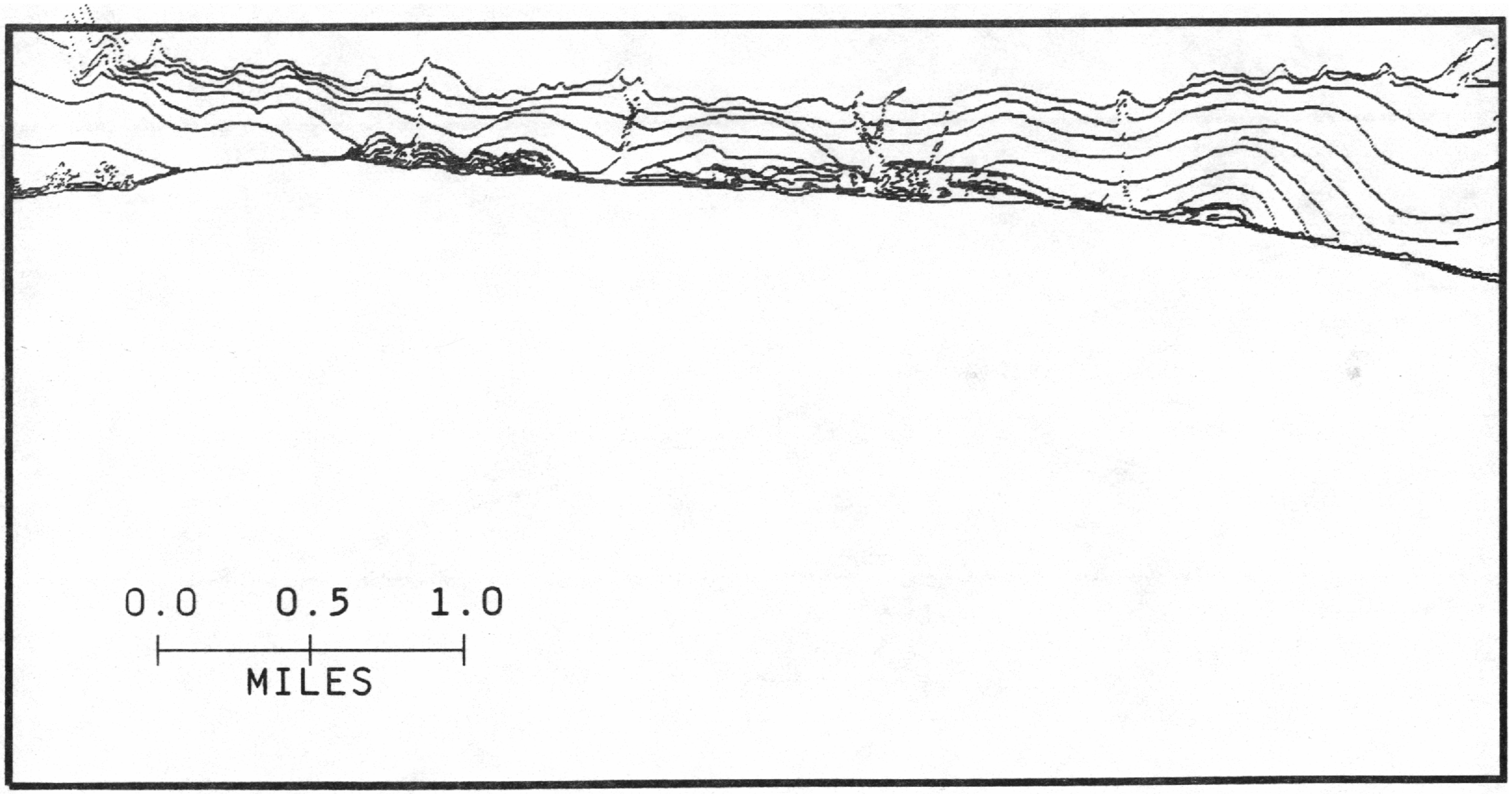


Figure 115. Interpolated data points for the San Onofre region in 1889.

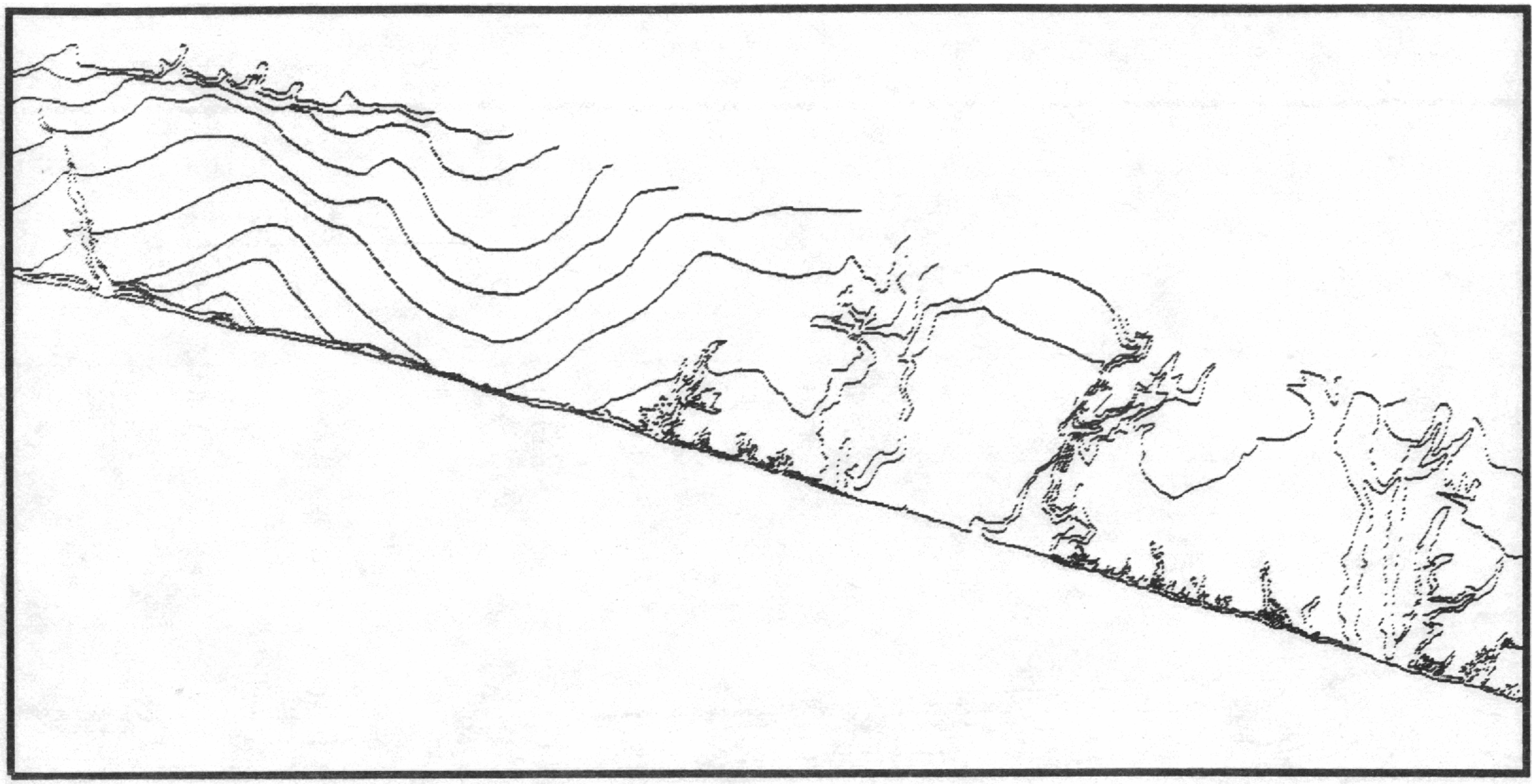


Figure 116. Interpolated data points for the Camp Pendleton region in 1889.

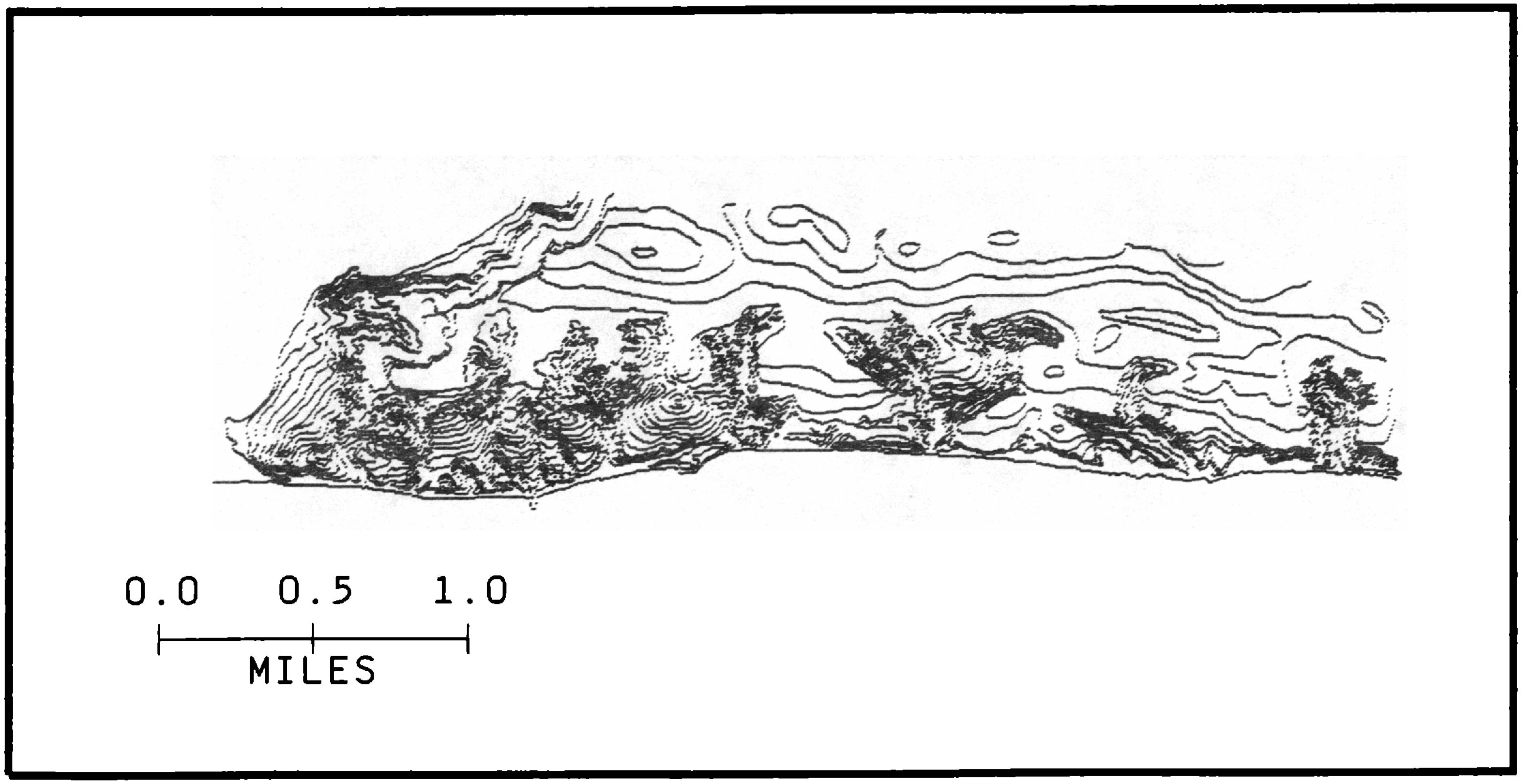


Figure 117. Interpolated data points for the Torrey Pines region in 1889.

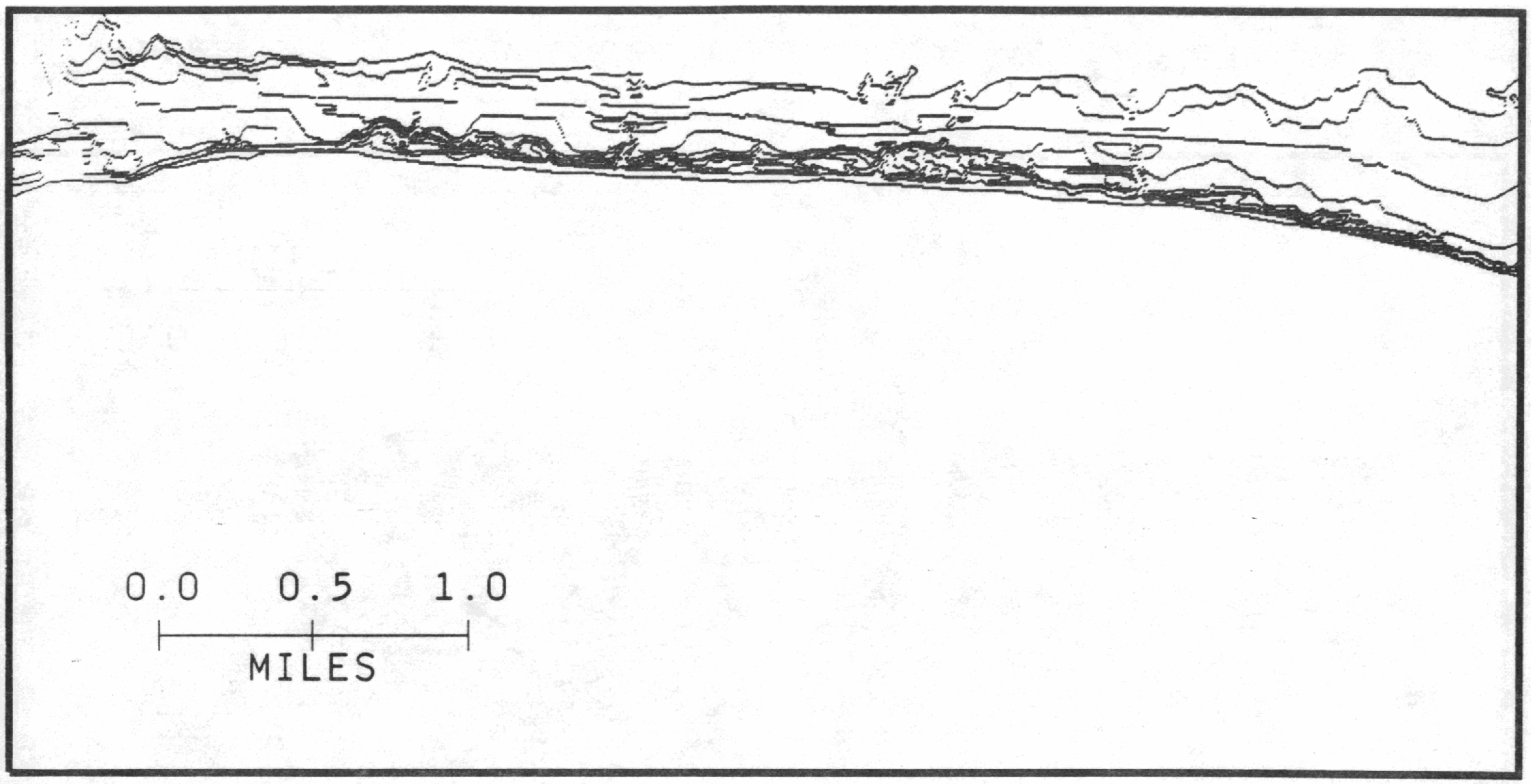


Figure 118. Interpolated data points for the San Onofre region in 1968.

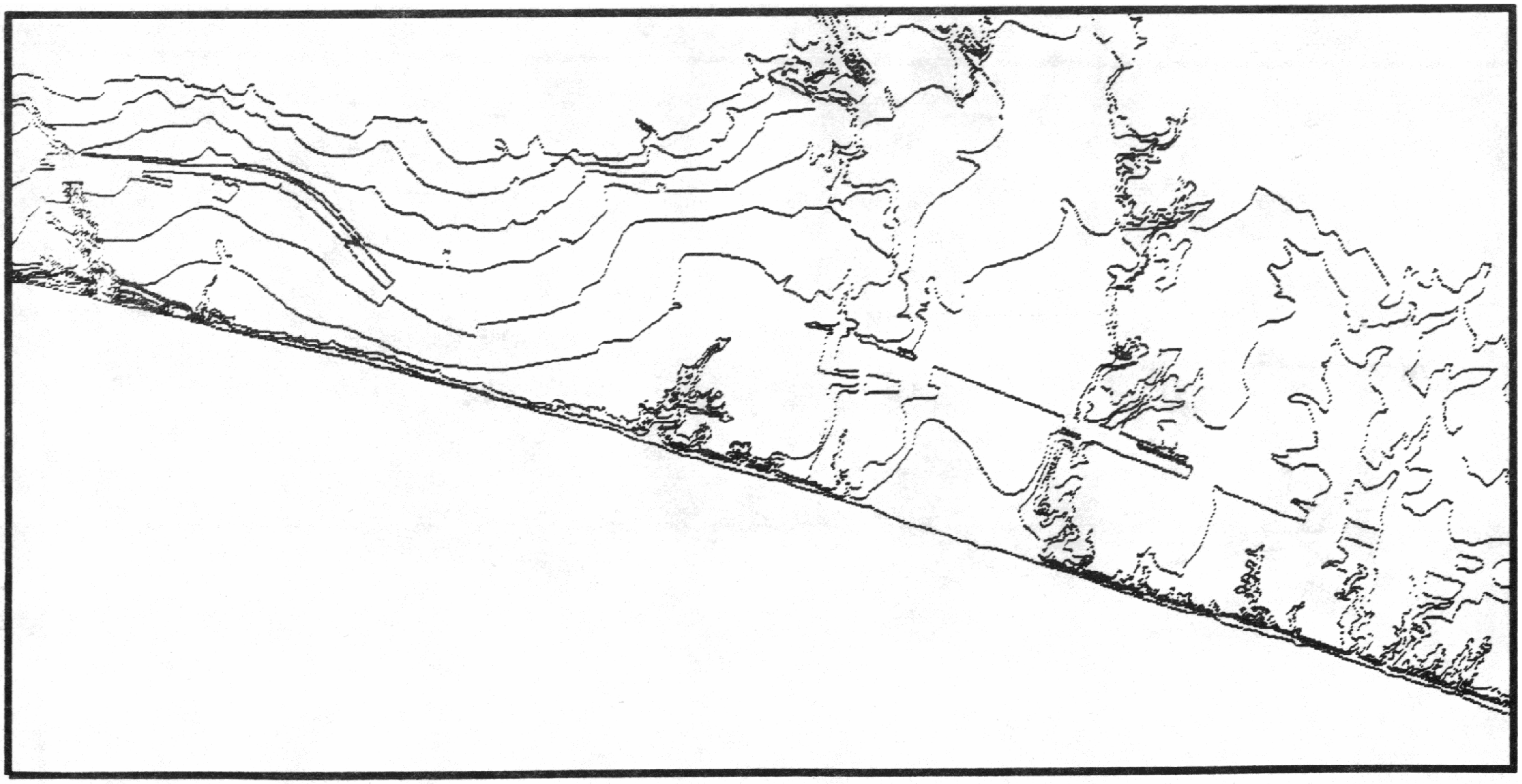


Figure 119. Interpolated data points for the Camp Pendleton region in 1968.

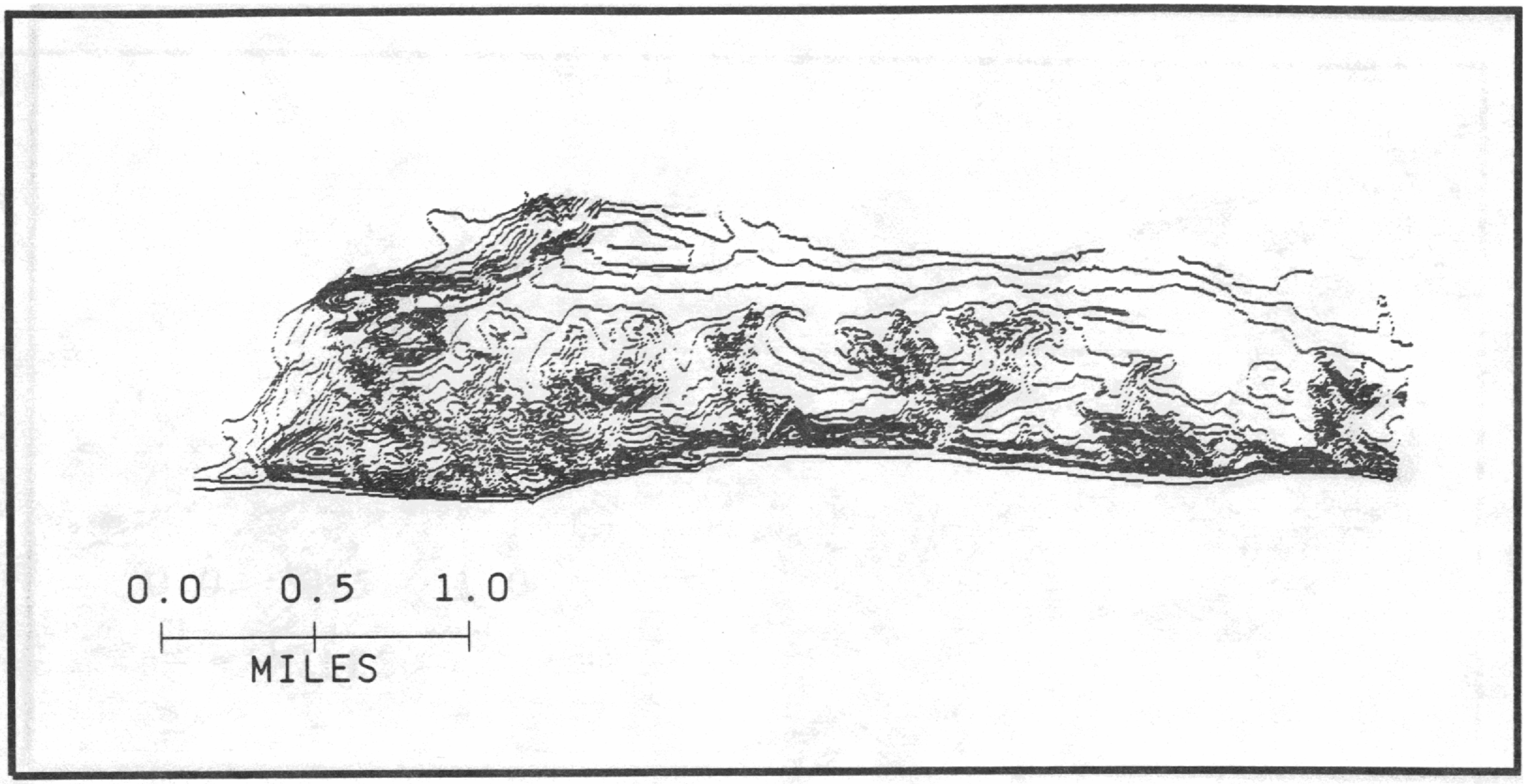


Figure 120. Interpolated data points for the Torrey Pines region in 1968.

7.9 The final step in gridding is to calculate for each column in the matrix, the elevation (Z) at each row (Y). Due to the nature of topographic contour maps, it is unknown how the topography varies from one drawn contour on the map to the next. Cliffs, gullies, knobs, boulders, and other features smaller than the usual 20 feet contour interval may never appear on the topographic map. As the map information is presented, one can only assume that the topography gradually changes from one drawn contour to the next. Therefore, for each row in the matrix, the elevation (Z) was interpolated at each row (Y) using a cubic spline interpolation method.

Calculating Change in Volume for Each Region

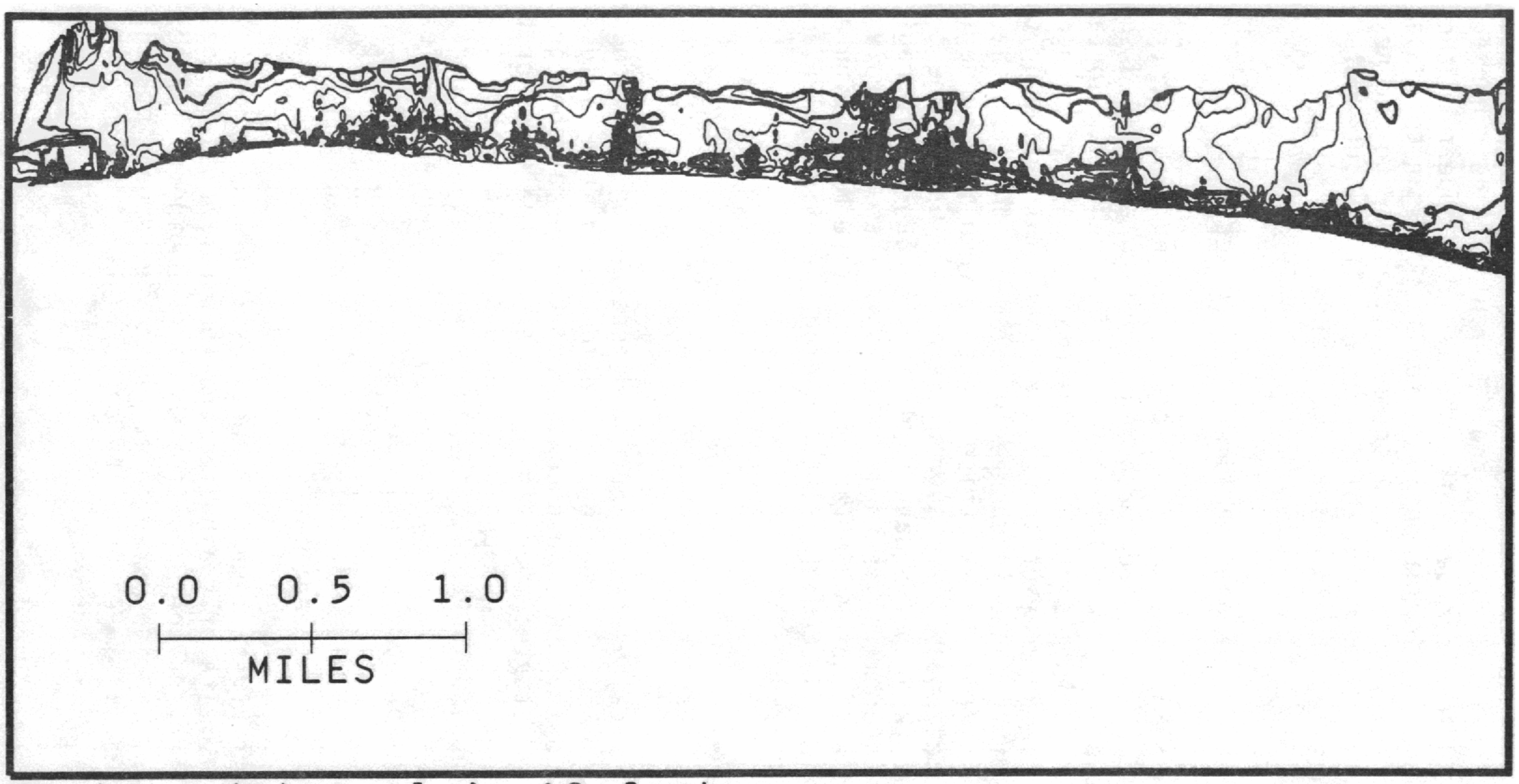
7.10 Subtracting each 1968 matrix from its corresponding 1889 matrix gives a matrix of elevation lost or gained for each region. Figures 121-123 show the change in elevation between 1889 and 1968 for the three regions. To calculate the change in volume for various parts of the matrix, the sum of change in elevation for each cell in an area of the matrix can be multiplied by the area. To show lateral differences in change in volume, both along the coast, and as one travels inland, the three matrices were divided into subregions. Figure 124 shows the location of these subregions as well as average change in volume in units of cubic yards per square yard, for the San Onofre region. Table 2 shows the same information in table form as well as total volume lost for each subregion, and averages and totals for the entire map. Figure 125 and table 3 shows this for the Camp Pendleton region, and figure 126 and table 4 shows this for the Torrey Pines region.

Possible Sources of Error

7.11 The results of the calculations presented here are only as good as the data that were entered. The 1889 maps were hand contoured from field observations, whereas the 1968 maps were contoured from aerial photographs, where parallax tends to distorted the information around the edges of the photographs. Paper onto which the maps are printed or photocopied can stretch. As described above, the topography in between drawn contours is unknown, but is assumed to be linear. Features smaller than the 20 feet contour interval of the maps remain undefined.

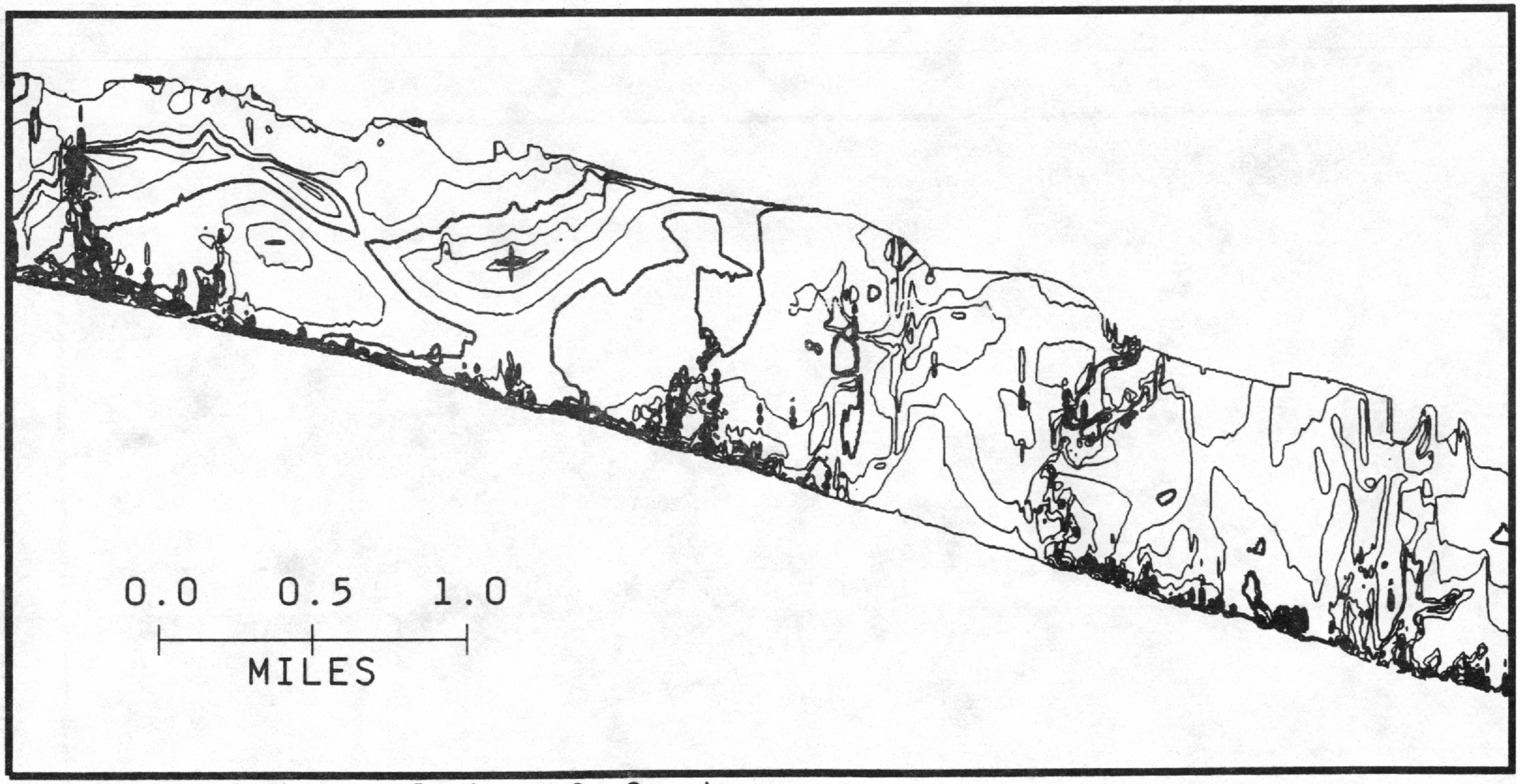
Sediment Yield

7.12 Field measurements of stratigraphic sections (Kuhn and others, 1987) were combined with the results of grain-size analyses performed by the Southern Pacific Laboratory of the U.S. Army Corps of Engineers (Tables 5 to 7), and a weighted average was computed to estimate the percent of sediment coarser than silt (0.0625 mm) in each of the appropriate stratigraphic sections (Table 8).



Contour interval is 10 feet

Figure 121. Map showing the change in elevation for the San Onofre region from 1889 to 1968.



Contour interval is 10 feet

Figure 122. Map showing the change in elevation for the Camp Pendleton region from 1889 to 1968.

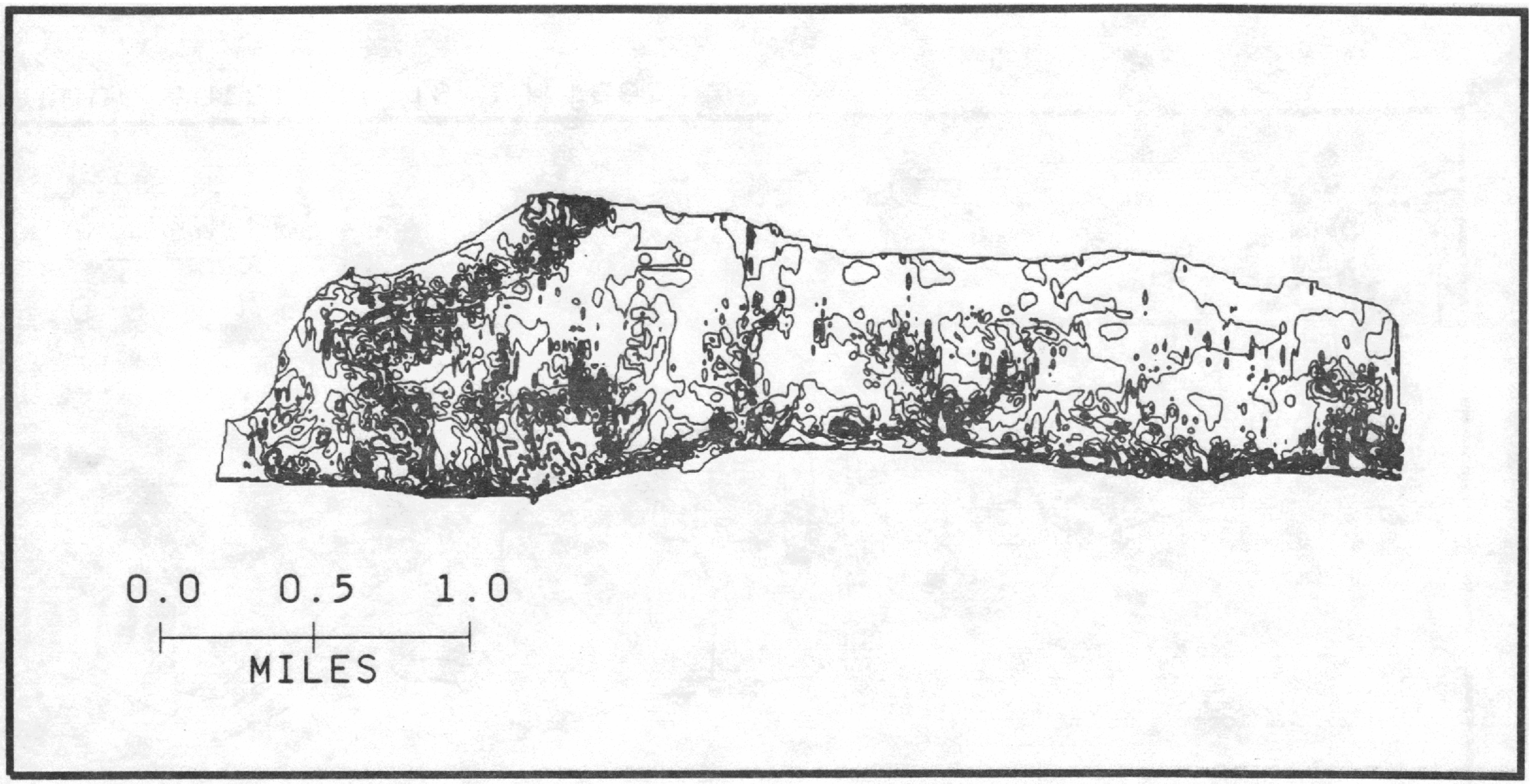


Figure 123. Map showing the change in elevation for the Torrey Pines region from 1889 to 1968.

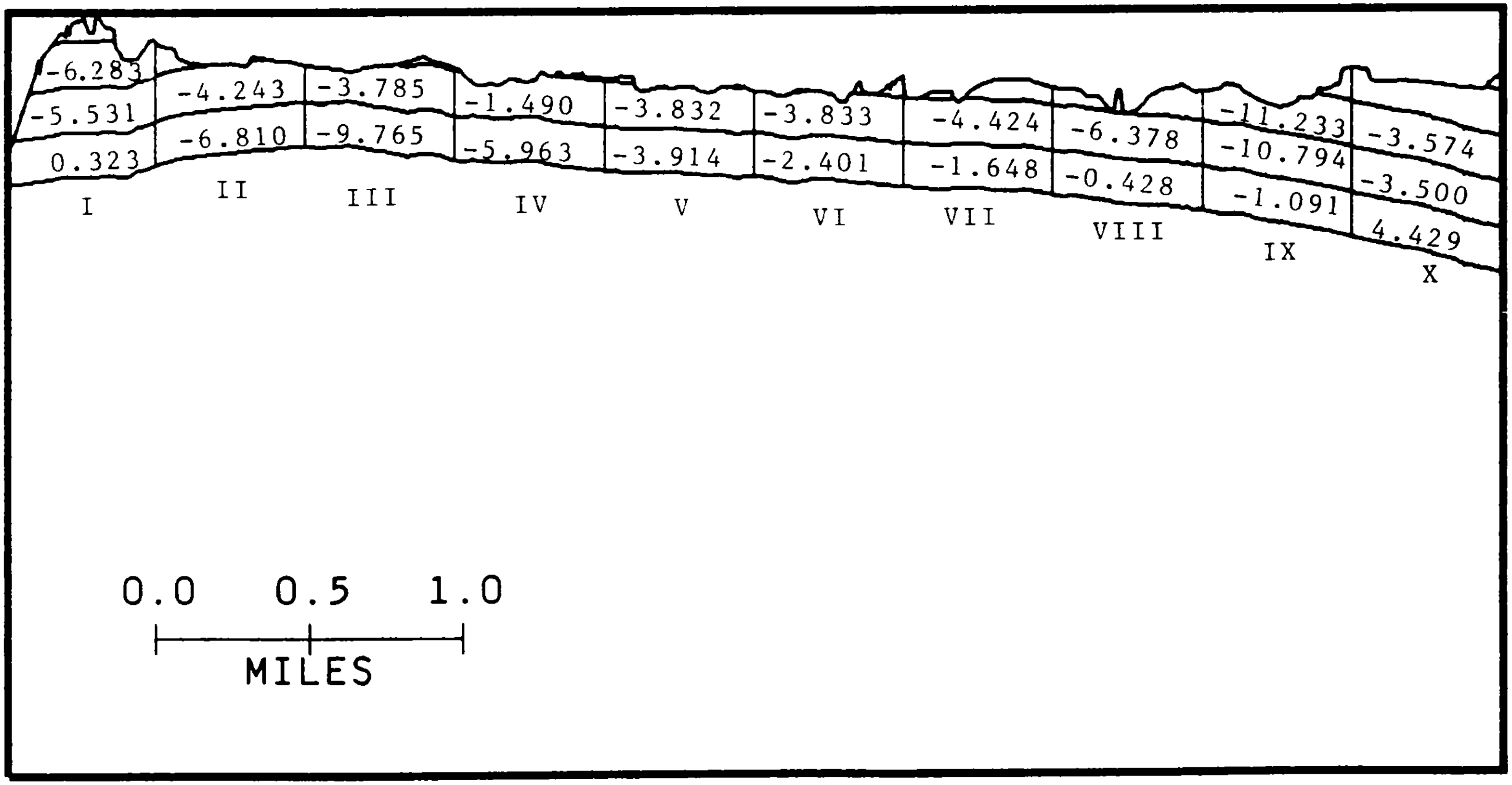


Figure 124. Average volumetric changes per cell (cubic yards per square yard) from 1889 to 1968 for the San Onofre region. Cell values are for the area from the coast to 250, 500 and 750 yards inland. Regions one through ten (Table 2) are shown by Roman numerals.

Table 2. Average volumetric change in millions of cubic yards and in cubic yards per square yard for the San Onofre region from 1889 to 1968.

San Onofre

VOLUME LOST IN MILLIONS OF CUBIC YARDS

X REGION	0 - 250	250 - 500	500 - 750
1	0.065	-1.052	-0.923
2	-1.372	-0.854	-0.039
3	-1.967	-0.692	
4	-1.201	-0.276	
5	-0.788	-0.742	
6	-0.484	-0.757	
7	-0.332	-0.918	
8	-0.086	-1.329	-0.411
9	-0.220	-2.249	-1.860
10	0.892	-0.729	-0.745

AVERAGE VOLUME LOST IN CUBIC YARDS PER SQUARE YARD

X REGION	0 - 250	250 - 500	500 - 750
1	0.323	-5.531	-6.283
2	-6.810	-4.243	-1.905
3	-9.765	-3.785	
4	-5.963	-1.490	
5	-3.914	-3.832	
6	-2.401	-3.833	
7	-1.648	-4.424	
8	-0.428	-6.378	-5.130
9	-1.091	-10.794	-11.233
10	4.429	-3.500	-3.574

TOTAL -19.895 MILLION CUBIC YARDS

AVERAGE -4.050 CUBIC YARDS PER SQUARE YARD

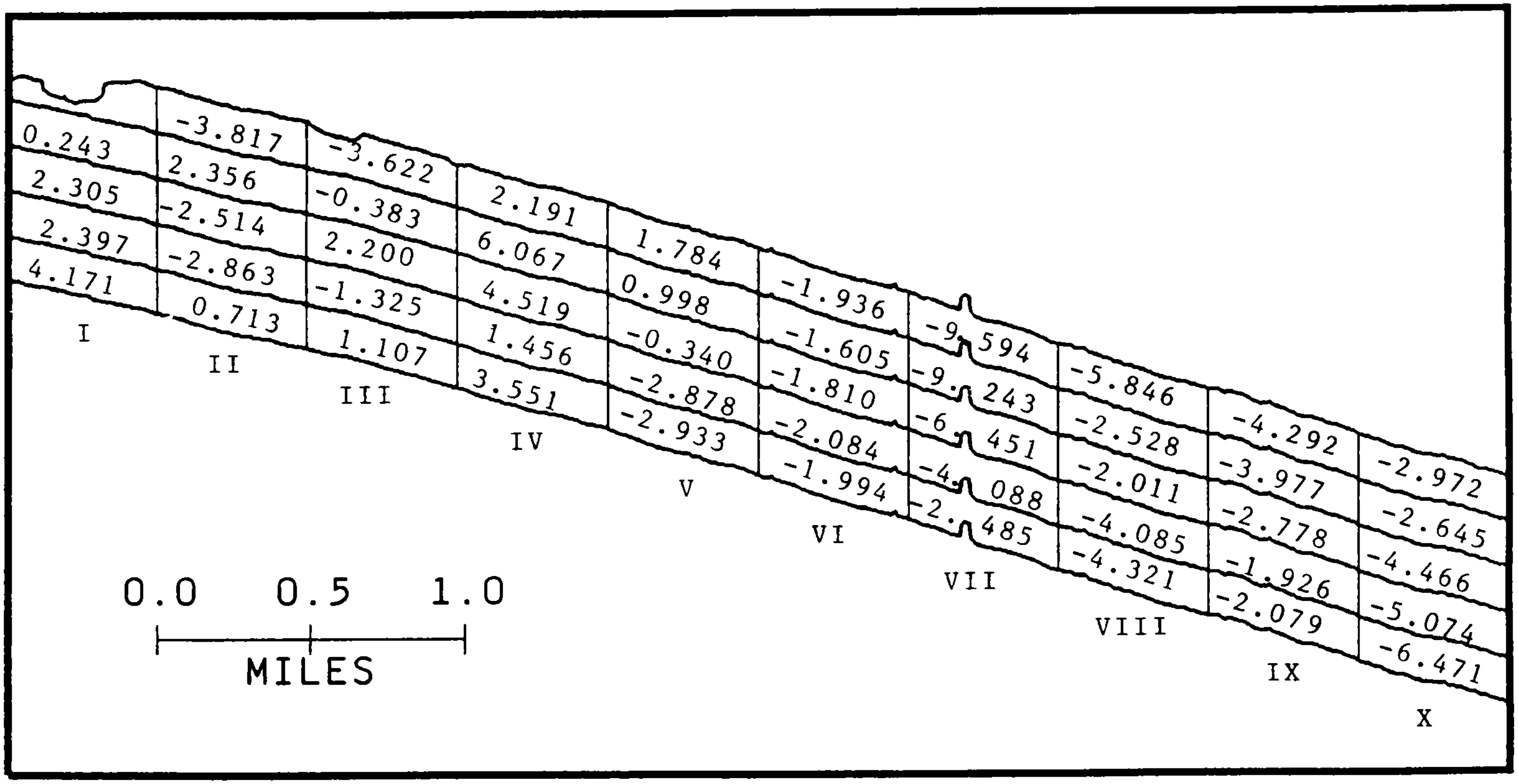


Figure 125. Average volumetric changes per cell (cubic yards per square yard) from 1889 to 1968 for the Camp Pendleton region. Cell values are for the area from the coast to 250, 500 and 750 yards inland. Regions one through ten (Table 3) are shown by Roman numerals.

Table 3. Average volumetric change in millions of cubic yards and in cubic yards per square yard for the Camp Pendleton region from 1889 to 1968.

Camp Pendleton

VOLUME LOST IN MILLIONS OF CUBIC YARDS

X REGION	0 - 250	250 - 500	500 - 750	750 - 1000	1000 - 1250 YARDS
1	0.840	0.499	0.480	0.051	
2	0.144	-0.596	-0.524	0.491	-0.795
3	0.223	-0.276	0.458	-0.080	-0.714
4	0.715	0.303	0.942	1.264	0.455
5	-0.591	-0.600	-0.071	0.208	0.372
6	-0.402	-0.434	-0.377	-0.334	-0.403
7	-0.500	-0.852	-1.344	-1.926	-1.999
8	-0.870	-0.851	-0.419	-0.527	-1.218
9	-0.419	-0.401	-0.579	-0.828	-0.894
10	-1.303	-1.057	-0.930	-0.551	-0.615

AVERAGE VOLUME LOST IN CUBIC YARDS PER SQUARE YARD

X REGION	0 - 250	250 - 500	500 - 750	750 - 1000	1000 - 1250 YARDS
1	4.171	2.397	2.305	0.243	
2	0.713	-2.863	-2.514	2.356	-3.817
3	1.107	-1.325	2.200	-0.383	-3.622
4	3.551	1.456	4.519	6.067	2.191
5	-2.933	-2.878	-0.340	0.998	1.784
6	-1.994	-2.084	-1.810	-1.605	-1.936
7	-2.485	-4.088	-6.451	-9.243	-9.594
8	-4.321	-4.085	-2.011	-2.528	-5.846
9	-2.079	-1.926	-2.778	-3.977	-4.292
10	-6.471	-5.074	-4.466	-2.645	-2.972

TOTAL -17.219 MILLION CUBIC YARDS

AVERAGE -1.679 CUBIC YARDS PER SQUARE YARD

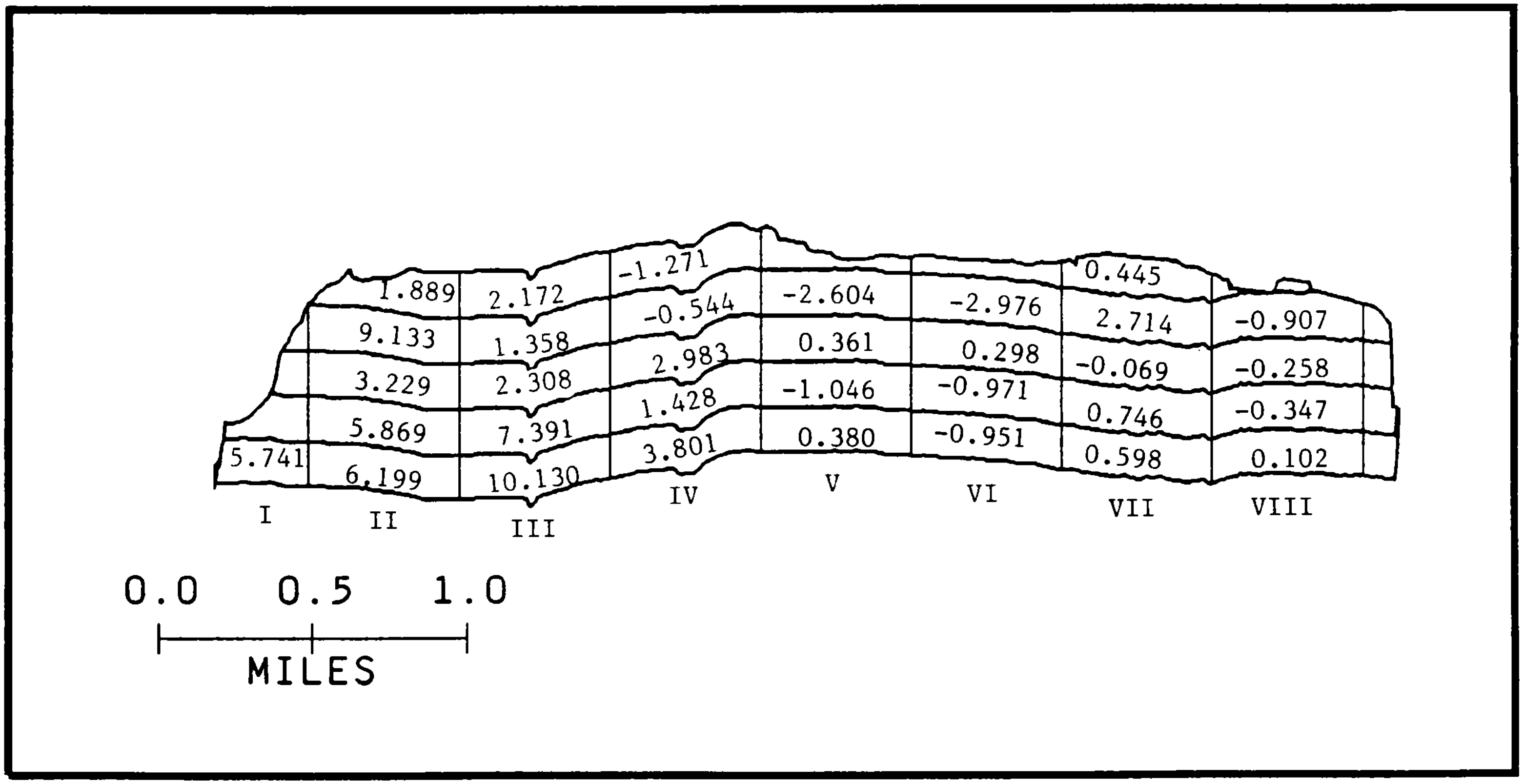


Figure 126. Average volumetric changes per cell (cubic yards per square yard) from 1889 to 1968 for the Torrey Pines region. Cell values are for the area from the coast to 250, 500 and 750 yards inland. Regions one through ten (Table 4) are shown by Roman numerals.

Table 4. Average volumetric change in millions of cubic yards and in cubic yards per square yard for the Torrey Pines region from 1889 to 1968.

TORREY PINES

VOLUME LOST IN MILLIONS OF CUBIC YARDS

X REGION	0 - 250	250 - 500	500 - 750	750 - 1000	1000 - 1250 YARDS
1	0.698	-0.216	0.147	0.117	
2	1.248	1.223	0.481	1.903	0.287
3	2.040	1.540	0.621	0.283	0.453
4	0.765	0.297	0.075	-0.113	-0.261
5	0.077	-0.218	0.062	-0.542	-0.242
6	-0.191	-0.202	-0.014	-0.620	-0.213
7	0.120	0.155	-0.054	0.565	0.073
8	0.021	-0.072	0.156	-0.183	
9	-0.095	0.044	0.090	-0.004	

AVERAGE VOLUME LOST IN CUBIC YARDS PER SQUARE YARD

X REGION	0 - 250	250 - 500	500 - 750	750 - 1000	1000 - 1250 YARDS
1	5.741	-2.454	3.229	6.023	
2	6.199	5.869	2.308	9.133	1.889
3	10.130	7.391	2.983	1.358	2.172
4	3.801	1.428	0.361	-0.544	-1.271
5	0.380	-1.046	0.298	-2.604	-2.640
6	-0.951	-0.971	-0.069	-2.976	-2.569
7	0.598	0.746	-0.258	2.714	0.445
8	0.102	-0.347	0.750	-0.907	
9	-2.133	1.062	2.288	-0.144	

TOTAL 10.30100 MILLION CUBIC YARDS

AVERAGE 1.369619 CUBIC YARDS PER SQUARE YARD

Table 5. Results of grain-size analyses for the San Onofre area.

SAMPLE	ELEV.	PHI	MM	SD	SKEW	KURT
SO1A2	3.0F	1.6800	0.3121	0.9395	0.4855	2.8772
SO1A6	51.5F	2.6225	0.1624	0.7387	-1.5578	6.0176
SO1A7	62.0F	2.2025	0.2173	1.1946	-0.9167	2.4127
SO1A8	73.0F	-0.3575	1.2812	2.3875	-0.5826	2.2512
SO1A10	102.0F	-1.1600	2.2346	2.1710	0.2767	2.1769
SO1B1	3.0F	1.6575	0.3170	0.9583	0.3606	2.5965
SO1B5	26.0F	2.5075	0.1759	0.7335	-1.3715	5.2280
SO1B8	59.0F	-1.0750	2.1067	2.8547	0.0723	1.4873
SO2A1	17.0F	-0.2300	1.1728	3.3920	-0.0409	1.3550
SO2A6	73.0F	-1.4525	2.7368	2.5248	0.6920	2.4536
SO2A7	230.0F	-0.0150	1.0105	1.9757	0.3956	2.1544
SO2B7	67.0F	-0.7575	1.6906	2.7383	0.1028	1.7442
SO2C3	50.0F	-1.0850	2.1214	2.4063	0.7590	2.6696
SO2C8	81.0F	-0.8975	1.8628	3.0613	0.3963	1.7156
SO2C2	12.0F	1.4450	0.3673	2.3955	-1.1727	3.2389
SO2C5	20.0F	2.7225	0.1515	0.6642	-2.3327	10.1906
SO2C7	42.2F	2.5775	0.1675	0.7397	-1.1537	5.5080
SO2C8	76.8F	-1.5450	2.9180	1.6319	0.0219	2.2670
S2C10	93.2F	-1.4025	2.6436	2.3087	0.8092	2.7374
SO3A3	26.5F	0.0125	0.9914	2.3104	-0.4164	1.8892
SO3A5	39.2F	1.2200	0.4293	0.6337	-0.0126	3.5581
SO3A8	89.2F	-1.2975	2.4580	2.4675	0.5976	2.4820

Table 6. Results of grain-size analyses for the Camp Pendleton area.

SAMPLE	ELEV.	PHI	MM	SD	SKEW	KURT
CP1B2	6.0F	-0.8875	1.8500	2.7385	0.0018	1.5714
CP1B7	49.0F	1.8700	0.2736	1.5287	-0.1982	2.8645
CP1B9	52.0F	2.0250	9.2457	1.2891	0.2773	1.9109
CP1C2	15.0F	2.4725	0.1802	0.6818	-0.5587	2.6854
CP1C3	16.3F	2.5700	0.1684	0.8125	-1.4991	5.2083
CP1C4	18.4F	1.7900	0.2892	1.2149	-0.1915	1.3837
CP1C5	21.0F	-0.5375	1.4515	2.0965	-0.5512	2.5307
CP1C7	29.0F	2.7625	0.1474	1.7075	-1.3277	3.8132
C1C10	37.0F	-0.4925	1.4069	2.3541	-0.0170	2.1065
CP2A2	21.0F	-0.3450	1.2702	1.7338	0.1210	2.7939
CP2A6	32.0F	2.8850	0.1354	1.2301	-1.5088	5.1963
CP2A9	46.0F	1.3650	0.3882	1.4170	0.2929	3.0341
CP2A5	13.0F	2.4075	0.1885	0.6242	-0.9061	6.0024
CP2C2	14.0F	1.6100	0.3276	1.4745	-0.7347	3.8054
CP2C3		-0.9775	1.9691	2.2550	0.1711	2.0819
CP2C5	34.0F	2.5325	0.1728	1.3778	-0.9880	3.9194
CP2C7	42.0F	2.1025	0.2329	1.0829	-0.4592	4.8677
CP2C9	47.0F	1.1625	0.4467	1.8043	-0.7761	3.5771
CP3A2	5.0F	1.6025	0.3293	0.8945	0.1143	2.3934
CP3A9	25.0F	1.5550	0.3403	0.9770	1.5186	4.6108
CP3B2	15.5F	0.7000	0.6156	0.6892	0.8156	2.6351
CP3B3	20.0F	3.4025	0.0946	0.5487	-3.6968	20.2671
CP3B5	23.0F	2.6750	0.1566	0.9230	-1.7791	5.5910
CP3B7	31.0F	1.5425	0.3433	1.3902	-1.0458	3.2337
CP3B9	43.0F	1.4700	0.3610	0.5090	0.0064	3.8536
CP3C1	3.0F	0.7800	0.5824	1.1577	0.1965	4.2345
CP3C6	24.0F	1.9375	0.2611	0.9959	-0.7115	2.6168
CP4A1	5.8F	1.7200	0.3035	0.8072	0.3219	3.1430
CP4A3	13.3F	3.3425	0.0986	0.6525	-3.0761	12.9642
CP4A8	82.0F	1.3725	0.3862	2.1522	-0.9732	3.1189
CP4B2	6.0F	1.4300	0.3711	0.8545	0.4707	2.8928
CP4B4	12.0F	-0.6300	1.5476	2.6787	-0.0217	1.7780
CP4C1	6.0F	1.6450	0.3197	0.7493	0.7284	3.5023
CP4C2	12.0F	1.3800	0.3842	0.8892	0.7701	3.1719
CP4C5	21.5F	0.6625	0.6318	1.3520	0.7953	3.3229
C4C10	96.0F	1.0325	0.4889	2.7105	-0.3846	1.7679

Table 7. Results of grain-size analyses for the Torrey Pines area.

SAMPLE	ELEV.	PHI	MM	SD	SKEW	KURT
TP1A3	24.0F	2.8525	0.1385	0.7142	-0.7504	4.3516
TP1A4	40.0F	2.8000	0.1436	0.8109	0.1864	1.8482
TP1A6	54.0F	2.6100	0.1638	0.7118	-0.0713	2.8150
TP1A7	101.0F	2.5675	0.1687	0.8177	0.3889	2.1994
T1A10	205.0F	3.4325	0.0926	0.6460	-1.7910	9.1318
TP1B1	13.5F	3.4175	0.0936	0.7027	-1.2253	3.8508
TP1B2	70.3F	3.4650	0.0906	0.4925	-1.0136	4.5309
TP1B3	149.0F	-1.3450	2.5403	3.1277	0.3928	1.4214
TP1B4	169.3F	2.7550	0.1481	0.8132	0.2681	1.9060
TP1B5	203.0F	2.0800	0.2365	0.8298	0.4799	4.0165
TP1B6	257.0F	2.9150	0.1326	0.7248	0.0218	1.8779
TP1B7	290.0F	3.3500	0.0981	0.6215	-0.7655	3.4624
TP1B8	307.0F	3.4900	0.0890	0.3408	-0.2356	2.6252
TP1B9	332.0F	2.6650	0.1577	1.0602	-0.5659	2.8945
T1B10	354.0F	2.2050	0.2169	1.2412	0.0642	1.9352
TP2A1	26.0F	3.4075	0.0942	0.8206	-1.7817	6.4270
TP2A2	78.0F	-0.2325	1.1749	3.0560	-0.3091	1.3925
TP2A3	118.0F	2.3600	0.1948	1.1404	-0.0024	2.3253
TP2A5	150.0F	2.1425	0.2265	0.6023	0.8321	4.3578
TP2A7	225.0F	3.9125	0.0664	0.2655	-3.7280	17.9647
TP2A8	227.0F	2.2325	0.2128	0.9691	-0.1706	3.3750
TP2A9	247.0F	2.5500	0.1708	1.9378	-1.6236	4.3955
T2A10	263.0F	2.2900	0.2045	0.6826	0.1031	3.5580
TP2C3	17.0F	3.7975	0.0719	0.4057	-1.9366	5.6029
TP2C7	111.0F	3.5375	0.0861	0.5054	-0.7421	2.5448
T2C10	140.0F	3.4150	0.0938	0.5812	-0.6692	2.7295
TP3A2	18.0F	2.1375	0.2273	0.6941	-0.0829	3.9066
TP3A3	30.0F	1.6100	0.3276	0.8988	0.0924	2.3965
TP3A4	51.0F	1.3750	0.3856	1.4403	-0.1367	3.5947
TP3A5	70.0F	1.3150	0.4019	0.9237	1.5208	5.4630
TP3A6	82.0F	1.6100	0.3276	1.0014	0.8092	3.3960
TP3A7	97.0F	2.3050	0.2024	1.3227	0.1003	1.5936
TP3A9	143.0F	1.9800	0.2535	1.0414	0.3985	2.5415
TP3B1	2.0F	3.0025	0.1248	0.6833	-0.1986	1.9045
TP3B2		3.3100	0.1008	0.6336	-0.4472	2.0124
TP3B3	15.0F	2.4500	0.1830	0.7525	-0.1223	2.4070
TP3B7	36.0F	2.2575	0.2091	0.9024	0.0102	2.3077
T3B10	161.0F	1.6450	0.3197	1.6749	0.1534	1.7076

Table 8. Percentage of sediment coarser than silt (0.0625 mm) in each of the stratigraphic sections measured within the areas where volumetric changes from 1889 to 1968 were computed.

Stratigraphic Section	Percent Coarser-Grained than Silt (0.0625mm)	Cell in which stratigraphic section occurs
SAN ONOFRE AREA		
SO-SS-3A	29.4	III
SO-SS-3B	84.0	IV
SO-SS-3C	67.0	IV
SO-SS-2A	72.5	VII
SO-SS-2B	97.1	VII
SO-SS-2C	100.1	VII
SO-SS-1C	85.0	VIII
SO-SS-1B	79.4	VIII
SO-SS-1A	82.3	IX
CAMP PENDLETON AREA		
CP-SS-4A	44.0	I
CP-SS-4B	53.0	I
CP-SS-4C	53.0	I
CP-SS-3A	35.7	III
CP-SS-3B	52.7	IV
CP-SS-3C	52.6	IV
CP-SS-2A	46.4	VII
CP-SS-2C	64.3	VII
CP-SS-2B	77.4	VIII
TORREY PINES AREA		
TP-SS-3B	65.5	III
TP-SS-3C	40.0	IV
TP-SS-3A	53.5	V
TP-SS-2C	12.5	VII
TP-SS-2B	18.8	VII
TP-SS-2A	56.0	VII
TP-SS-1C	10.6	VIII
TP-SS-1B	23.8	VIII

7.13 Assuming that the mean of these obtained percentages (Table 8) is representative of the cell in which the stratigraphic section(s) occurs, and that the grand mean of all cells within a major region such as San Onofre, Camp Pendleton or Torrey Pines is representative of the strata throughout the coastal portion of that region, the following percentages were computed. Approximately 71.8 percent of the strata examined in the Camp Pendleton region is coarser than silt, 54.2 percent of the strata in the Camp Pendleton region is coarser than silt, and 42.4 percent of the strata in the Torrey Pines region is coarser than silt. Multiplying the total sediment yield for San Onofre, Camp Pendleton, and Torrey Pines (Tables 2, 3 and 4) by the appropriate percentage of sediment coarser than silt (Table 8) produces minimum volumes of 14.285, 9.333 and 4.368 million cubic yards of coarse-grained sediment that was delivered to the coastline from 1889 to 1968. These values sum to 27.986 million cubic yards.

8. MINERALOGIC COMPOSITION OF COASTAL CLIFFS AND BLUFFS

Introduction

8.1 The area from Dana Point to the U.S.-Mexico International Border consists of gently westward-sloping, narrow coastal plains which contain several actively-eroding canyons that are almost normal to the coastline. Adjacent coastal bluffs and cliffs extend eastward to the foothills of the Peninsular Range and are assigned to the Peninsular Range Geomorphic Province. Faults encountered in the coastal cliffs extend from large, subparallel, northwest-trending faults within the central mountainous Peninsular region. The Peninsular Range Geomorphic Province is bounded to the north by the San Bernardino and San Gabriel Mountains of the Transverse Ranges. The Salton Sea, a large trough formed by two subparallel faults, is the eastern limit. Geomorphologically, the western boundary of the Peninsular Range Province is the California Continental Borderland.

8.2 The sampled locations in the study area from Dana Point to the U.S. -Mexico International border occur along coastal bluffs, including those portions of San Diego and Orange Counties that are located west of Interstate-5. Specific sample sites are concentrated in two major segments of this part of the California coastline. These two segments have significant coastal cliffs that contribute large volumes of sediment to the adjacent littoral zone (Osborne and Pipkin, 1983). These two segments contain numerous, large canyons and significant gullies that erode by rapid, episodic, and site-specific subaerial processes. Such erosional processes have been documented using aerial photographs (Kuhn and Shepard, 1984).

8.3 The northern coastal cliff segment extends for ten miles from San Onofre Creek south to the Santa Margarita River, and it includes San Onofre State Park and most of coastal Camp Pendleton. The second coastal cliff segment is located approximately twelve miles farther south of the San Onofre-Camp Pendleton segment. This two-mile segment is bounded by Torrey Pines State Reserve to the north and Scripps Institute of Oceanography to the south.

8.4 Although two major segments of contributing coastal cliffs and bluffs were sampled, the stratigraphic sections are assigned to three separate localities. The San Onofre locality contains three sample sites (Plate 2), which can be easily accessed by the trails within the San Onofre State Park. The four sample sites in the Camp Pendleton locality (Plate 2) are not included with the San Onofre sample sites, because they only can be accessed by entering U.S. Marine Corps property. The Torrey Pines locality has three sample sites (Plate 4); all of which can be accessed from Torrey Pines Municipal Beach.

8.5 Locations and mechanisms of potential cliff contribution and retreat are discussed by Kuhn and others (1987) to determine the magnitude of cliff erosion and possible sediment contribution to the littoral system of the beaches in the area. Samples were collected to determine which stratigraphic bodies are contributing sediment to the littoral zone. The ultimate purpose of sampling was to estimate the quantity of sediment being delivered to the littoral zones of local beaches. Grain-size and mineralogic data characteristic of the samples collected will provide additional information concerning the physical properties of the sand-contributing units exposed in the cliffs.

8.6 Thirty stratigraphic section were measured for the three sampling regions along the coastal cliffs of San Diego: San Onofre, Camp Pendleton, and Torrey Pines. Detailed stratigraphic sections and interpretations of associated depositional environments of these stratigraphic sections are presented in Kuhn and others (1987). A total of 69 petrographic analyses were performed by the Southern Pacific Laboratory of the U.S. Army Corps of Engineers on samples collected from 16 of the stratigraphic sections measured. The average mineral composition of the cliffs was plotted for each of the 16 stratigraphic sections to detect any major systematic trend of mineralogy along the coast (Figure 127). The heavy minerals were analyzed in a similar fashion (Figure 128). Factor analysis was performed for each of the the three regions on both the total mineralogy and the heavy mineralogy to identify any clusters by formation within a region. The resultant data were analyzed by examining loadings on two factors. For regions with significant clusters, possible contributing factors are discussed.

Methods

8.7 Each stratigraphic section was divided into its constituent units. After the grain size and sedimentary structures of the stratigraphic units were described, the major sand contributing units were identified. The mineralogical data supplied was divided into two sets. The first set represents the medium sand fraction (0.25 to 0.50 mm, Wentworth, 1922) of the total light and heavy mineral composition of each sample, and includes quartz, potassium feldspar, plagioclase feldspar, and the total heavy mineral suite. The second set represents only the heavy mineral fraction of each sample, and includes the following minerals: biotite, opaque minerals, actinolite, apatite, augite, biotite, epidote, composite particles, garnet glaucophane, glaucophane schist (a rock fragment), hornblende, hypersthene, olivine, opaque minerals, piedmontite, sphene, tournaline, zircon, and zoisite.

8.8 The samples within a given columnar section were averaged compositionally for each of the sixteen stratigraphic sections. This data was then used to construct plots of the total mineralogy and the heavy mineral assemblages. The data for each stratigraphic section represents the combined contribution as point source locations (stratigraphic sections) of the contributing coastal cliffs to the adjacent beach.

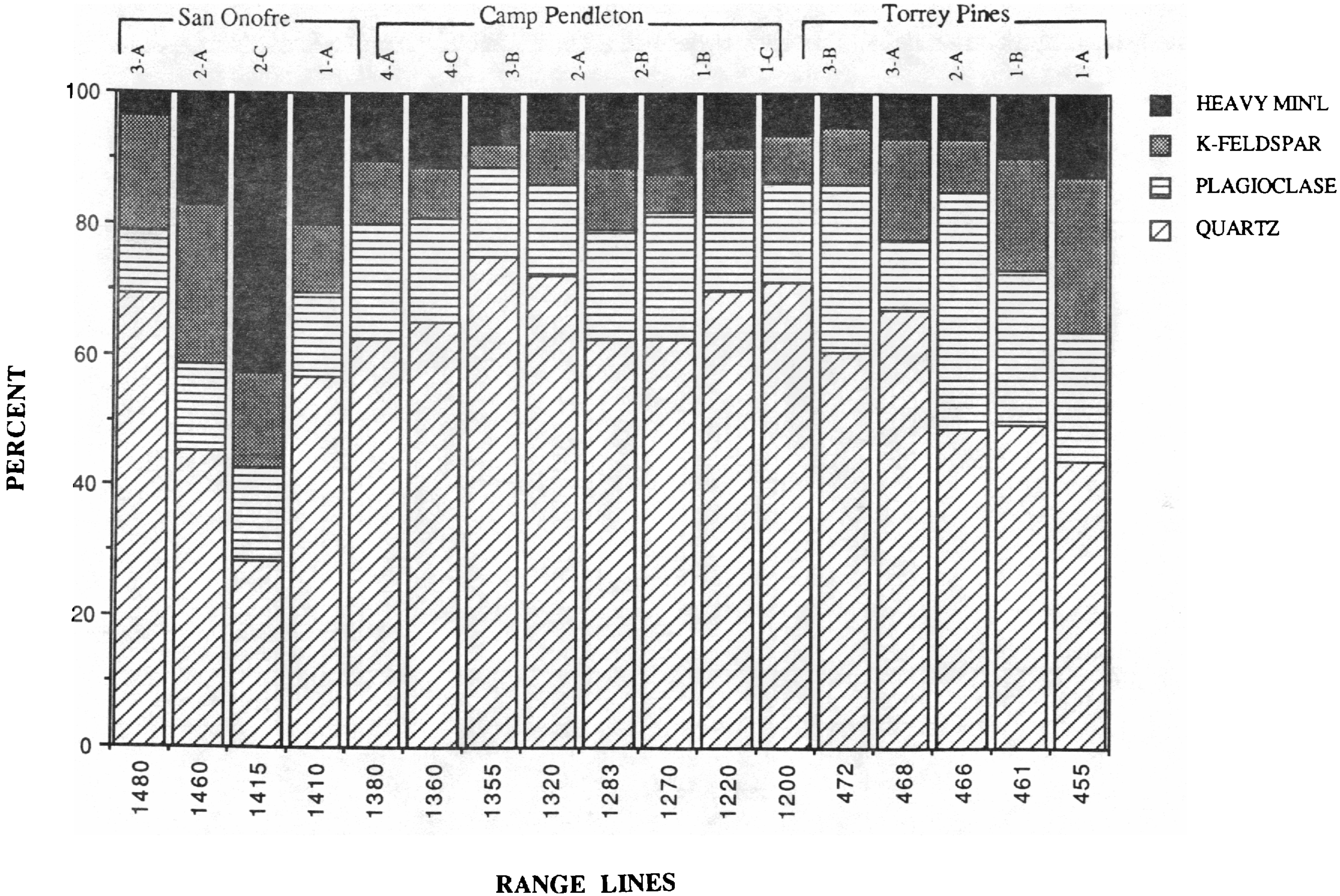


Figure 127. Average total mineral composition of coastal cliffs, 1986. Numbers along the abcissa refer to range lines.

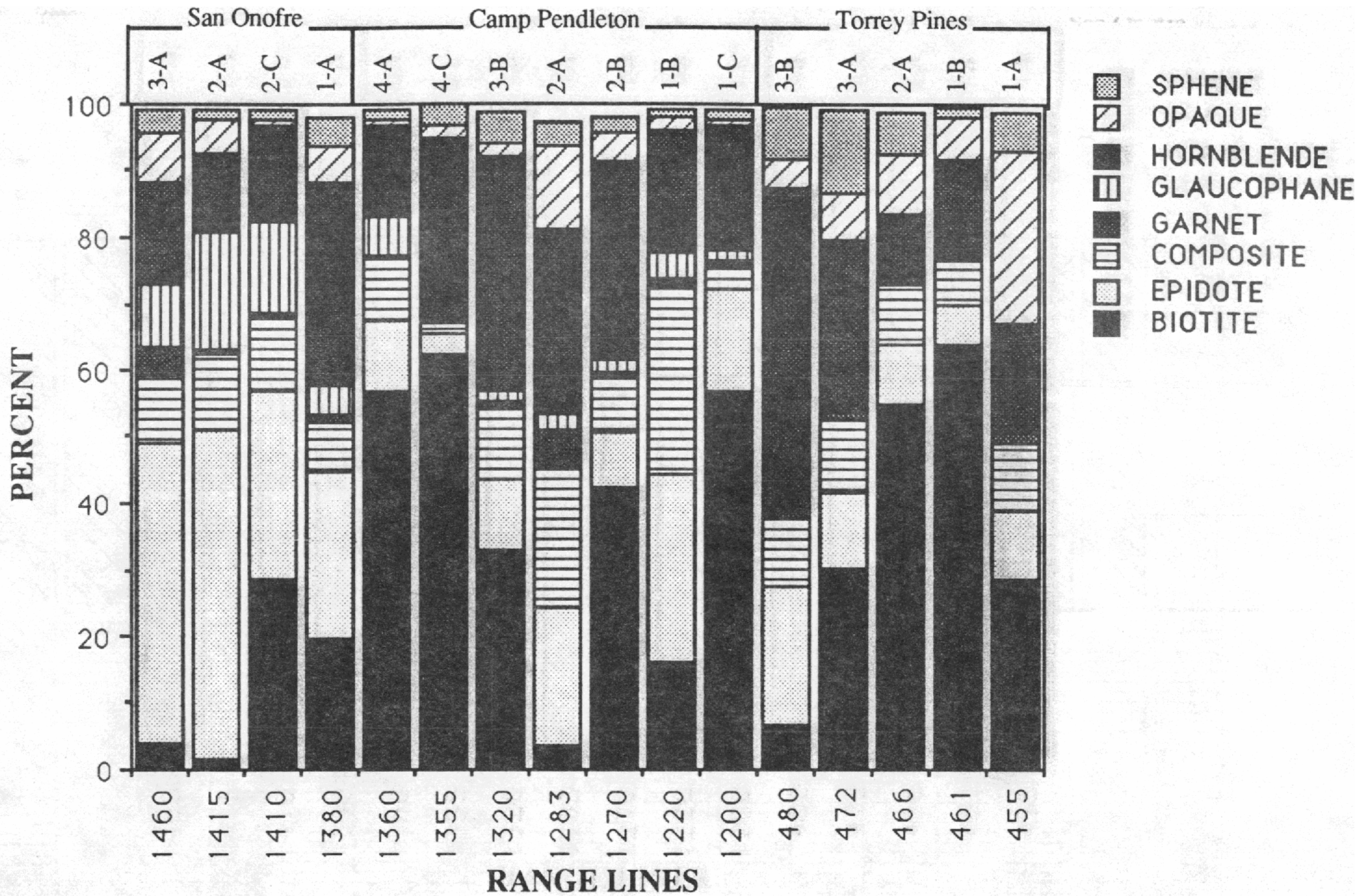


Figure 128. Average principal heavy mineral composition of coastal cliffs, 1986.

Sediment Sources

8.9 Inasmuch as all mineralogic materials in sediment and sedimentary strata are directly or indirectly derived from crystalline rocks of the earth's crust, it is necessary to consider (1) the ultimate crystalline source rocks and (2) the local fluvial and cliff sediment sources.

8.10 The 5 to 10 percent of the earth's surface that is mountainous supplies at least 80 percent of the siliciclastic sediment to modern depositional basins. Dams prevent bedload from being transported from the mountains to the basin. Furthermore, rates of denudation are directly proportional to relief, and, in general, it appears that streams draining areas of highest relief have the highest proportion of bedload (Blatt and others, 1980, p. 24-26). It is therefore appropriate to consider the crystalline terrains exposed at higher elevations as the dominant ultimate source rocks for the obtained sample set.

8.11 The Geologic Map of the Corona, Elsinore, and San Luis Rey Quadrangles, California (Larsen, 1948) shows that the basement complex consists of two principal units: (1) the Late Jurassic (Portlandian) Santiago Peak Volcanics and (2) the mid-Cretaceous plutonic rocks assigned to the southern California batholith, which intrudes the Santiago Peak Volcanics. The Santiago Peak Volcanics occur as an elongate belt of low-rank metamorphosed volcanic, volcaniclastic and sedimentary rocks that crop out from the southern edge of the Los Angeles basin southward into Mexico (Gray and others, 1971). Compositionally these rocks range from basalt to rhyolite, but are predominantly dacite and andesite. A number of low-rank metamorphosed, small gabbroic plutons, which were probably feeders for the volcanic strata, are included in the Santiago Peak Volcanics.

8.12 Plutonic rocks of the southern California batholith are generally quartz diorite and gabbro. The quartz diorite contains large phenocrysts of plagioclase and potassium feldspar, and hornblende and biotite are present in minor amounts. The gabbroic units are compositionally variable, but consist mostly of calcic feldspar and pyroxene, with minor amounts of quartz and biotite. Larsen (1948) named the principal units in the southern California batholith the Woodson Mountain Granodiorite, the Bonsall Tonalite, and the San Marcos Gabbro. Table 9 summarizes the modal mineralogic composition for the cliff and bluff sample set and the principal source rocks. The compositional data for the Woodson Mountain Granodiorite, Bonsall Tonalite and San Marcos Gabbro are from Larsen (1948). It is clear from Table 9 that crystalline rocks in the southern California batholith are capable of producing the major mineral assemblages present in the sample set. Available time does not permit an exhaustive literature search to document the presence of minor accessory minerals in these crystalline rocks; however, zircon, sphene and rutile commonly are associated with acid plutonic rocks; piedmontite and clinozoisite-epidote are associated with mafic igneous rocks; and glaucophane and actinolite-tremolite are metamorphic minerals.

Table 9. Modal mineralogic composition of the cliff and bluff sample set (n = 69) and principal ultimate source rocks. The values for quartz, potassium feldspar and plagioclase feldspar are expressed as percent of total mineralogy. The values for all other minerals are expressed as percent of the heavy mineral fraction.

Principal Detrital Minerals Identified in Sample Set	Cliff and Bluff Sample Set (%)	Woodson Mountain Granodiorite (%)	Bonsall Tonalite (%)	San Marcos Gabbro (%)
Quartz	59.31	33 (30-40)	20-25	4 (0-10)
Potassium Feldspar	11.13	20 (10-30)	4-15	Tr
Plagioclase Feldspar	19.61	41 (30-55)	55-60	59 (47-66)
Biotite	39.51	5 (1-8)	5-15	3 (0-6)
Opaque Minerals	5.25	Tr	Tr	3
Pyroxene	0.39	Tr	Tr	8 (0-28)
Augite	0.04	Tr	Tr	7 (0-17)
Hornblende	21.70	1 (0-2)	10	
Garnet	1.14		Tr	13 (1-42)
Zircon	0.15			
Sphene	4.26			
Rutile	0.00			
Piedmontite	0.08			
Clinozoisite-Epidote	16.00			
Actinolite-Tremolite	0.18			
Glaucophane	0.44			
Glaucophane Schist	2.57			

8.13 The occurrence of glaucophane, glaucophane schist and actinolite-tremolite reflects ultimate derivation from the Mesozoic metamorphic age (110 m.y.b.p.) Catalina Schist terrane, which consists of a glaucophane-rich, blueschist. Stuart (1979, p. 36) reports a diverse set of clast types, which occur in the San Onofre Breccia. These include clasts of (1) the blueschist facies, which is rich in glaucophane and contains quartz, albite and chlorite; (2) the glaucophanic greenschist facies, which is rich in epidote and contains albite; (3) the greenschist facies, which is rich in actinolite and contains epidote, albite and chlorite; (4) the quartz schist facies, which consists of foliated quartz with greenschist and abundant glaucophane; (5) the saussurite gabbro facies, which contains actinolite, zoisite, clinozoisite and albite; (6) the amphibolite facies which contains amphibole, zoisite and garnet; and (7) the serpentinite facies, which contains calcite, tremolite, chlorite and actinolite. Such terranes are exposed on Santa Catalina Island and the Palos Verdes Hills, and occur in the subsurface of the Los Angeles basin, but are not known to occur within the uplands associated with the southern California batholith. The San Onofre Breccia (Miocene) is the most extensive deposit containing Catalina Schist detritus (Stuart, 1979). Scattered exposures of this unit occur from Santa Cruz Island southeastwrd to the Laguna Beach-Oceanside area, and then again south of Tijuana. The San Onofre Breccia is exposed as a strike ridge extending from San Onofre Mountain near Dana Point almost to Oceanside, and this exposure as well as younger sedimentary strata exposed along the coastal cliffs may have served as the local source for the glacophane, glaucophane schist and perhaps the actinolite-tremolite grains present in the sample set.

The San Onofre Area

8.14 The San Onofre area (Plate 2), a 2.5 mile segment of coastline approximately 12.5 miles southeast of Dana Point, is characterized by reddish-brown Quaternary marine or nonmarine terrace and alluvial fan deposits, which range from 15 to 30 meters thick. Thick, horizontally-bedded Pleistocene and Pliocene(?) strata unconformably overly the Monterey Formation (Miocene) throughout this region (Ehlig, 1977). The basal unit varies from a diatomaceous, siltstone facies of the Monterey Formation at sample site 3 to a westward-dipping, cross-bedded, coarse-grained sandstone facies at sample site 2. Extensive landslide escarpments are present within the highly-fractured fine-grained facies of the Monterey Formation. This landsliding causes rapid, subaerial erosion of the overlying Quaternary strata.

8.15 The Quaternary strata contain thick siltstone units with several amalgamated, laterally-discontinuous, broad lenses of channel-fill, and thin beds of conglomerate. Angular clasts of metamorphic blueschist and greenschist facies dominate the composition of the pebble and cobble units, which range from cobble stringers 0.2 meters thick to conglomerate channels 4 meters thick. The clasts were ultimately derived from the Catalina Schist terrane, and are locally derived by resedimentation from the San Onofre Breccia (Ehlig, 1979). Generally, the resedimented cobbles and pebbles are subangular to subrounded, bladed clasts.

8.16 The post-Pleistocene geologic history in the San Onofre area is dominated by both eustatic sea level fluctuations and regional tectonic uplift, the geomorphic relation of ancient fluvial terraces which change facies to marine terraces is quite complex (McNey, 1979). Interfingering and reworking of fluvial and marine deposits make it difficult to differentiate fluvial and wave-cut marine terrace deposits. Consequently, the Quaternary units described in the stratigraphic sections are not assigned to a particular formation, but are referred to as unnamed marine or nonmarine terrace and alluvial deposits.

8.17 Discontinuous Pliocene sedimentation in shallow marine embayments and coastal streams (such as the characteristic Caspistrano Embayment) contributes to the topographic expression of younger marine terrace deposits (Kern, 1977). Inasmuch as the Pleistocene Epoch was characterized by marked sea level flucuations, Pleistocene clastic facies are present in the sea cliffs that reflect alternating periods of deposition and erosion (Kern, 1977). Localized sediment sources and sinks were created by faulting during the middle Pleistocene Epoch. The strata comprising the coastal plain dip slightly to the southwest, and are generally incised by wide streams filled with alluvium. Following local tectonic events, thick alluvial deposits within coastal fluvial channels record a general marine transgression in the San Diego area (Kern, 1977). The existence of paleosols can be significant for interpreting the cyclic sedimentation that occurred as a result of the submergence and emergence of the ancient southern California coastline during the Pleistocene Epoch (Shlemon, 1979).

8.18 Figure 127 shows the downcoast trends of the average total mineralogy per section; Figure 128 shows the downcoast trends of selected heavy minerals, and Figures 129 through 146 show these downcoast trends in greater detail. The coastal cliffs in the San Onofre region show a significant increase in quartz downcoast, trend is coupled with a reduction in plagioclase feldspar downcoast. There is no apparent trend for the overall heavy mineral assemblage, although there is a large peak of more than 40 percent heavy minerals at stratigraphic section SO-2-A. Epidote comprises almost fifty percent of the heavy mineral content at this location. The entire region has an enrichment of epidote, which decreases downcoast. There appears to be a slight increase of hornblende upcoast. Glaucophane schist and composite particles are present in relatively consistent amounts of ten percent within the cliffs. Biotite increases significantly, but not systematically, downcoast. The presence of epidote, glaucophane schist, and hornblende are indicative of a sediment source containing blueschist. Blueschist clasts occur in the San Onofre Breccia that crops out along the coastal cliffs and clasts of which occur in the marine and nonmarine terrace deposits. The more dense minerals and small percentage of biotite may represent a depositional environment characterized by relatively high mechanical energy.

8.19 Factor analysis was performed for the total mineral composition and the heavy mineral fraction using two factors (Figures 147 and 148). The Quaternary terrace deposits and Monterey Formation which crop out along the coastal cliffs in the San Onofre region show no significant statistical clusters of samples for the total mineralogy or heavy minerals. Factor

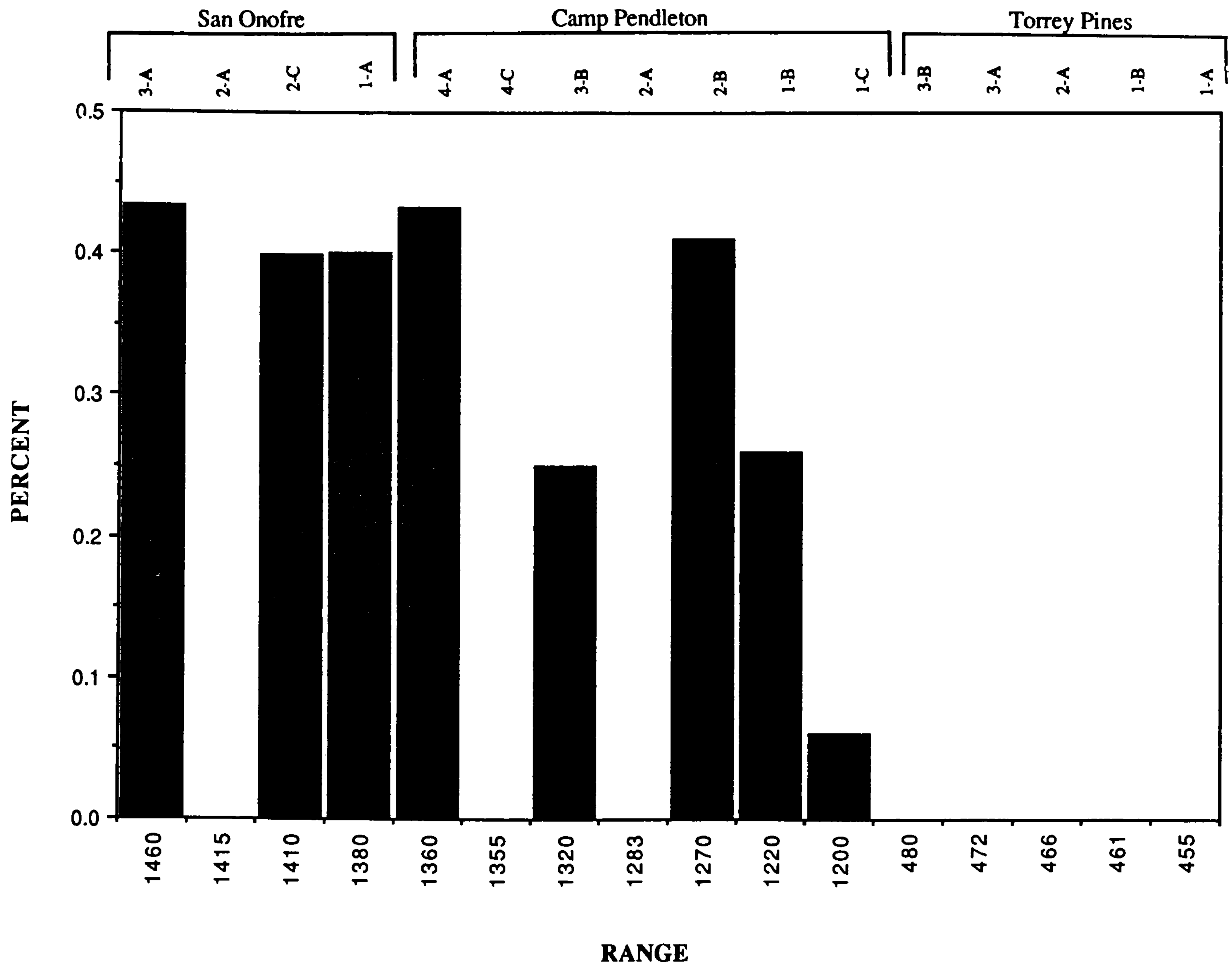


Figure 129. Percentage of actinolite present in 1986 cliff samples.

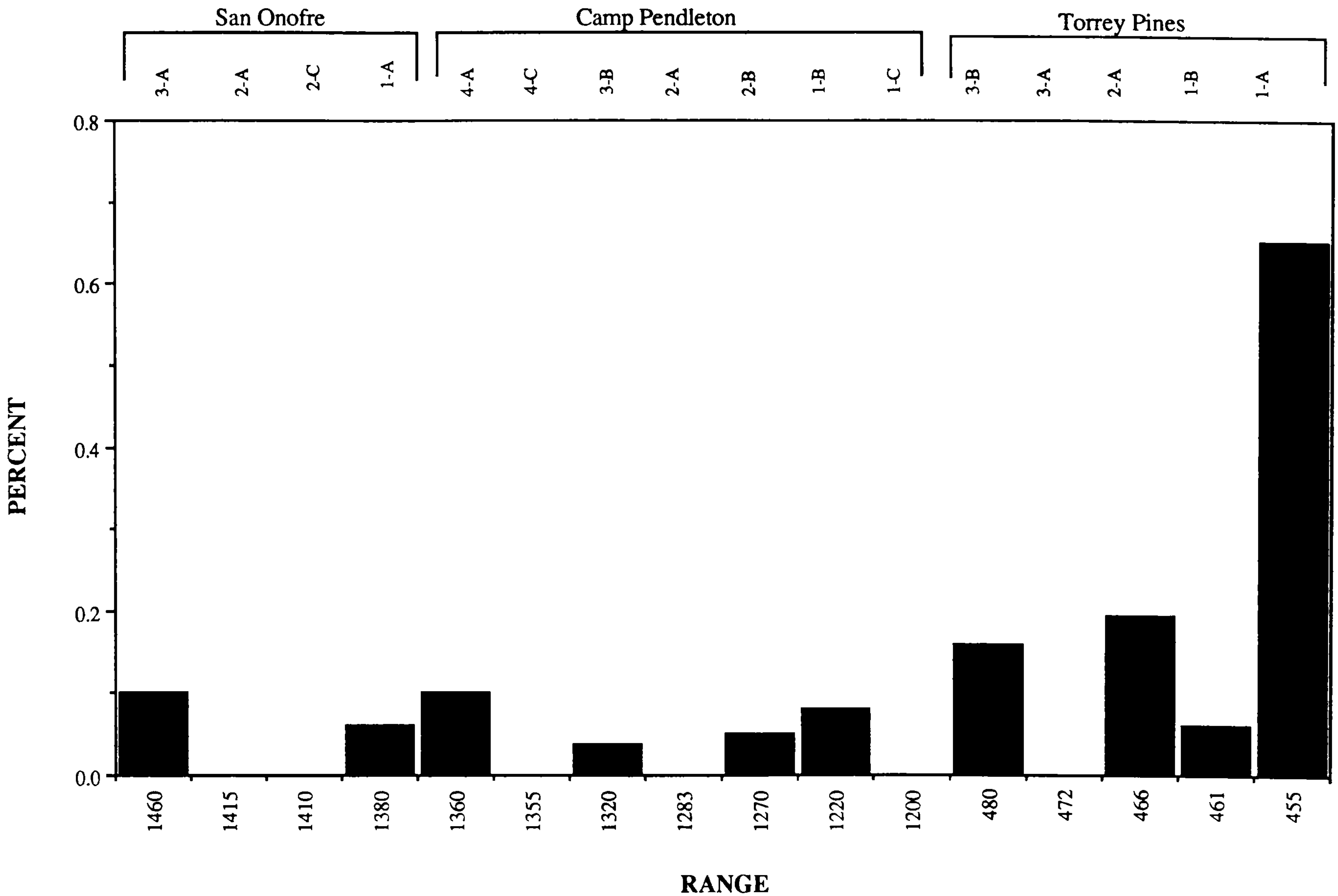


Figure 130. Percentage of apatite present in 1986 cliff samples.

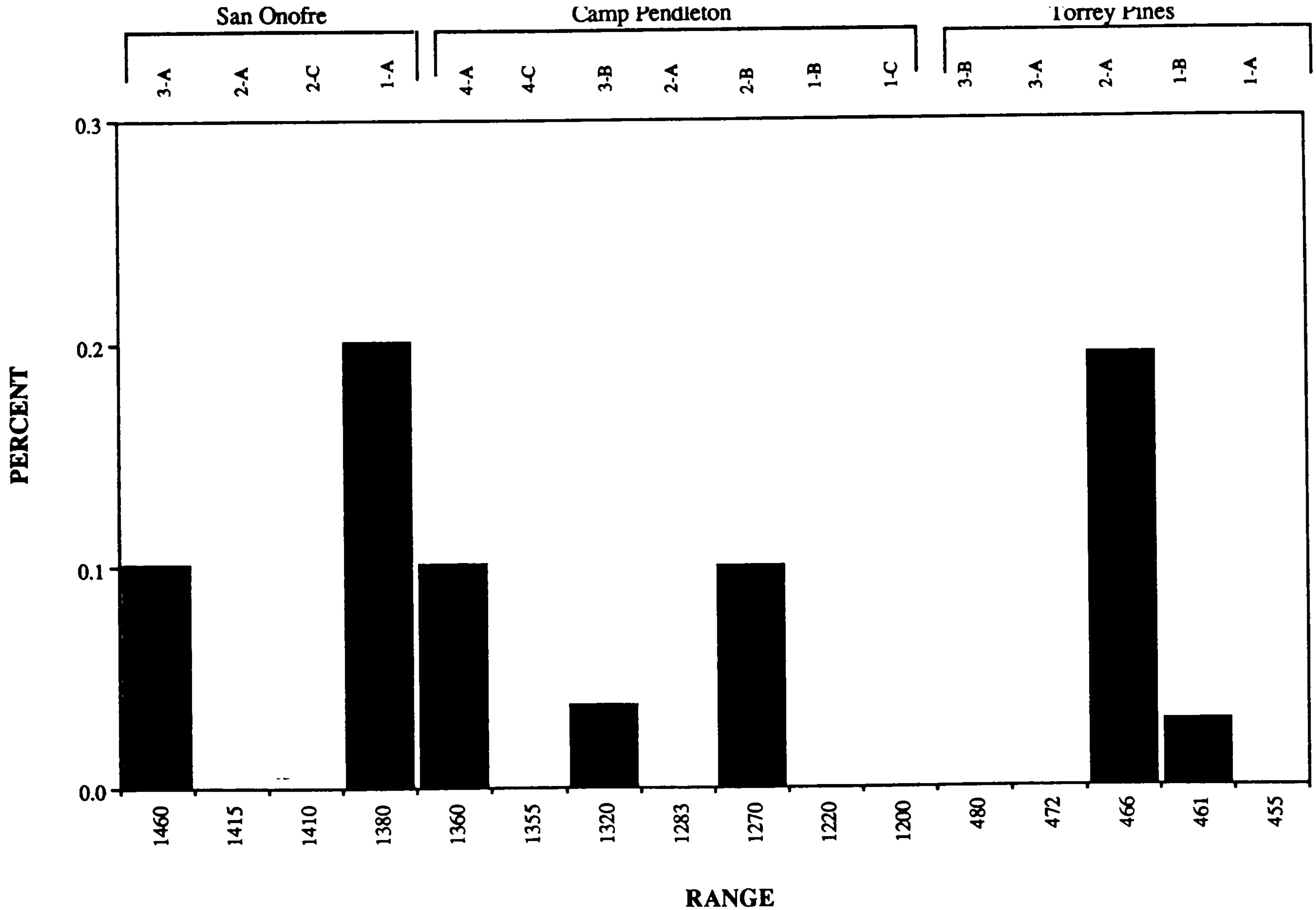


Figure 131. Percentage of augite present in 1986 cliff samples.

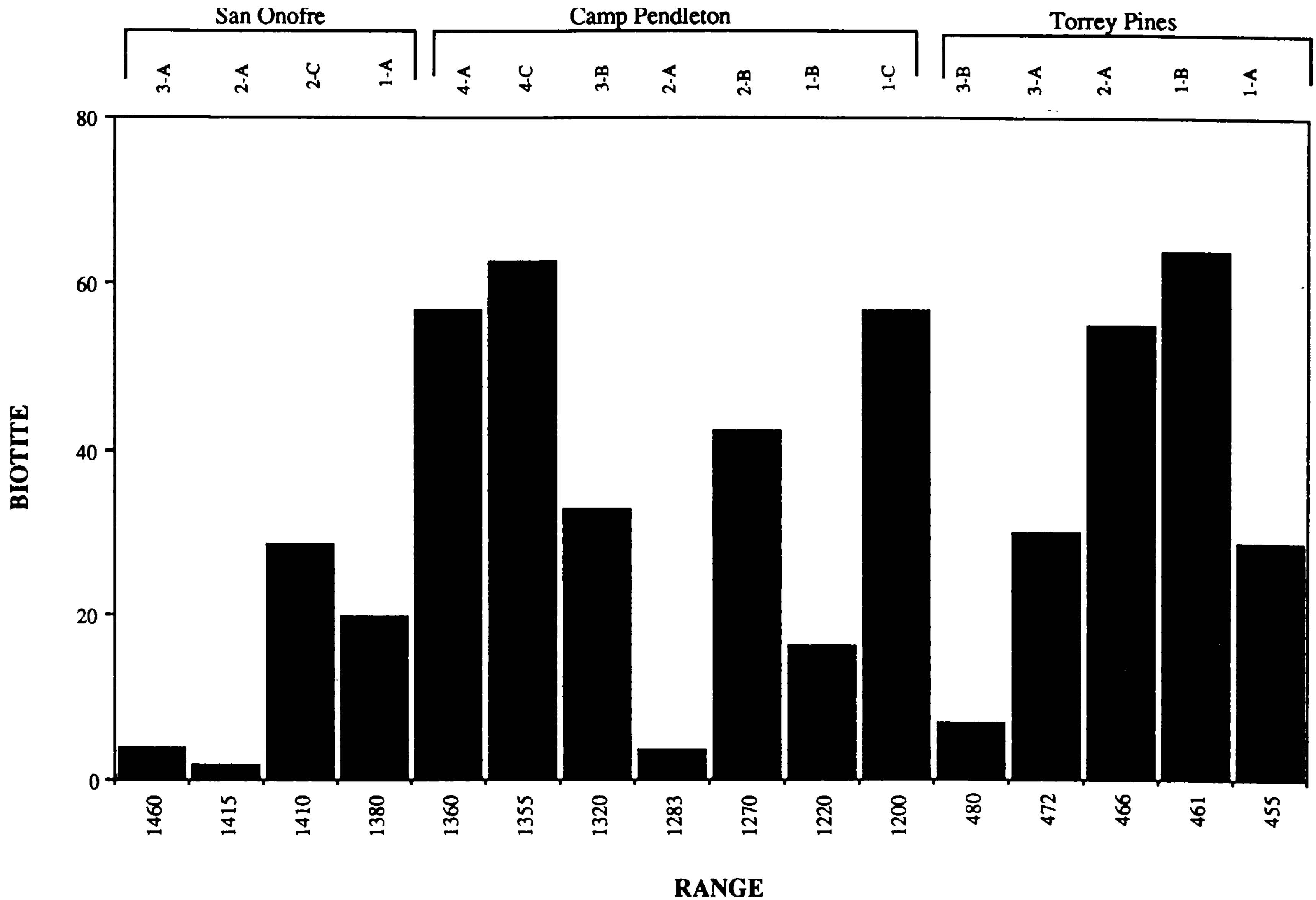


Figure 132. Percentage of biotite present in 1986 cliff samples.

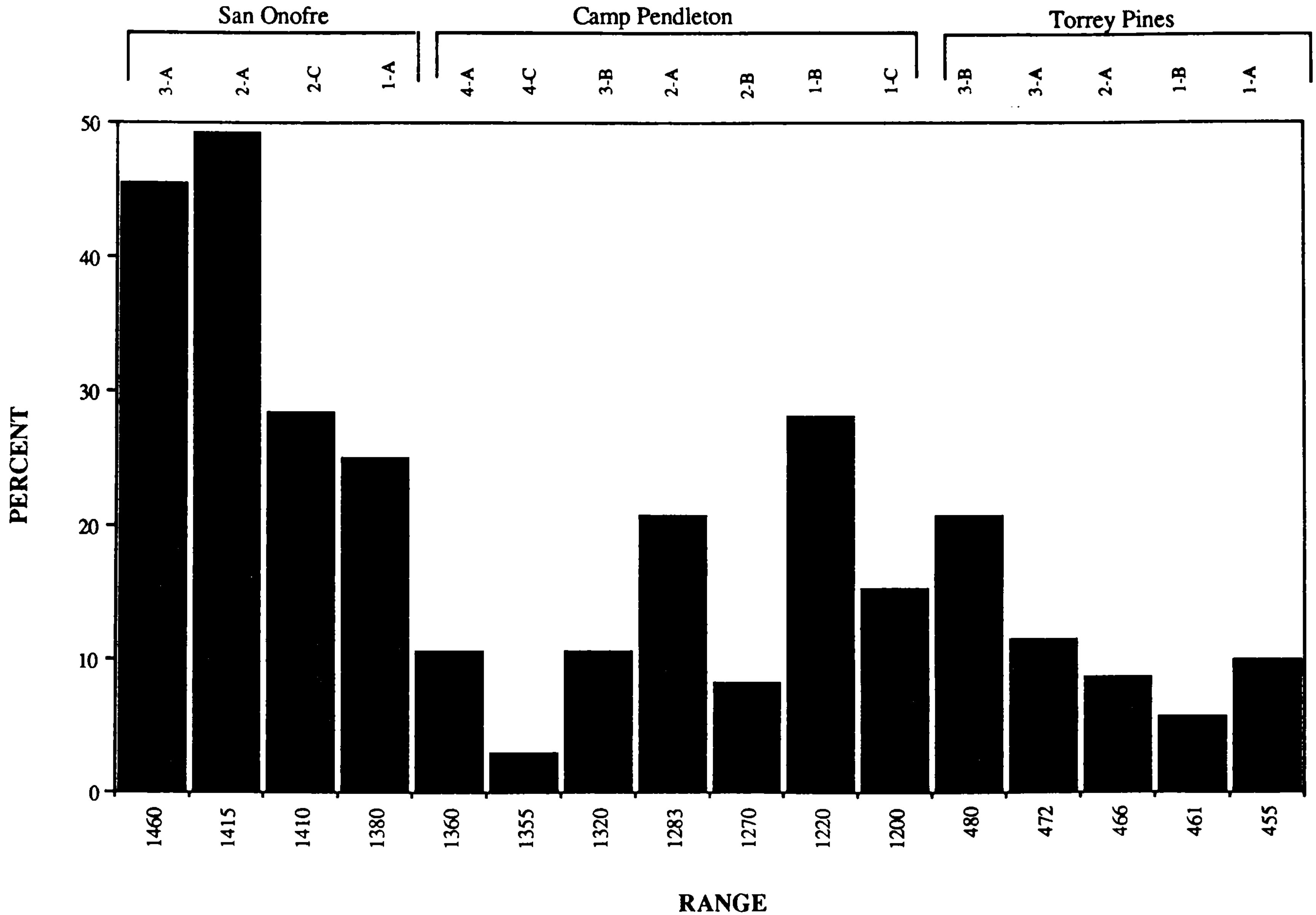


Figure 133. Percentage of epidote present in 1986 cliff samples.

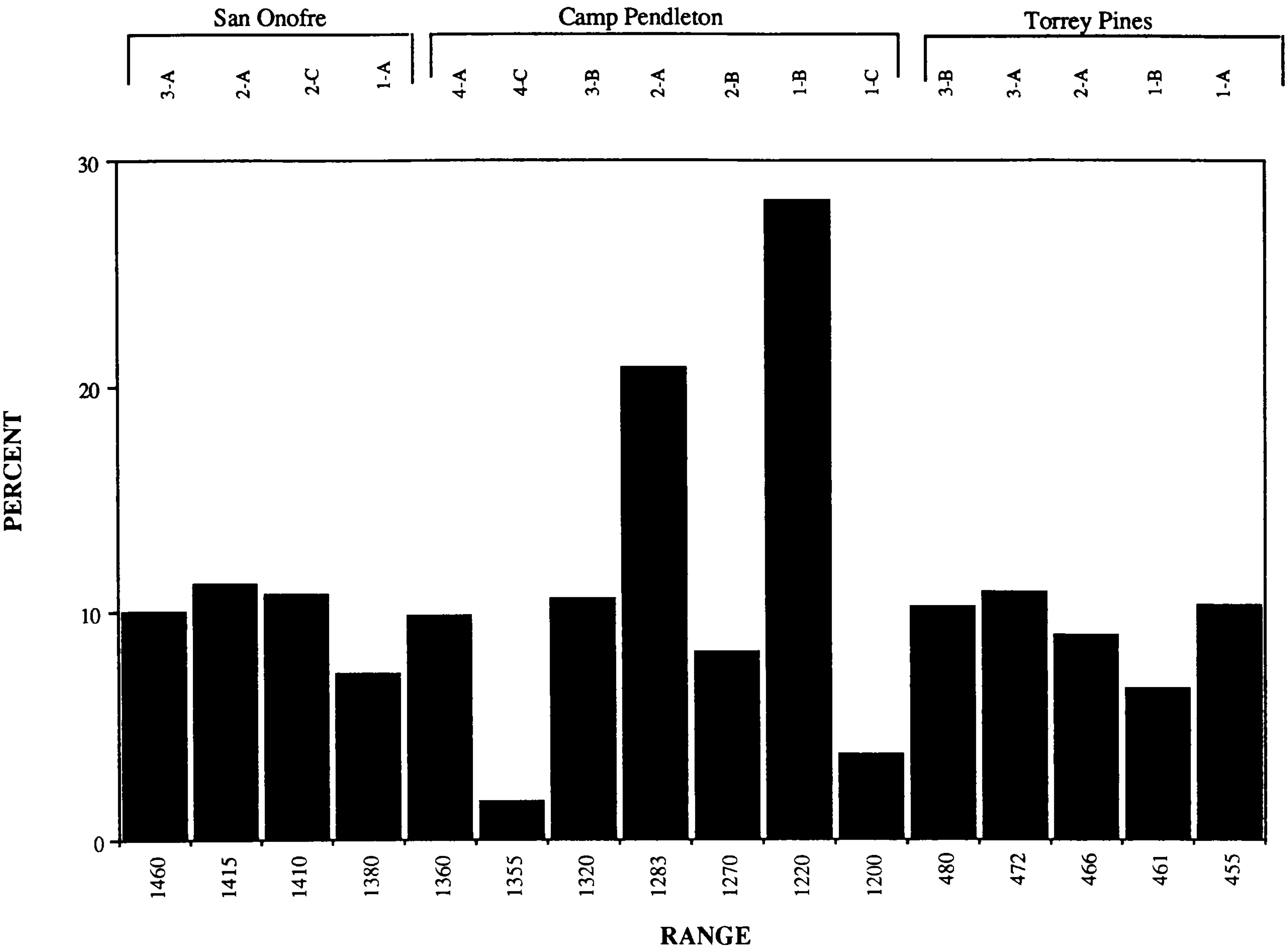


Figure 134. Percentage of composite particles present in 1986 cliff samples.

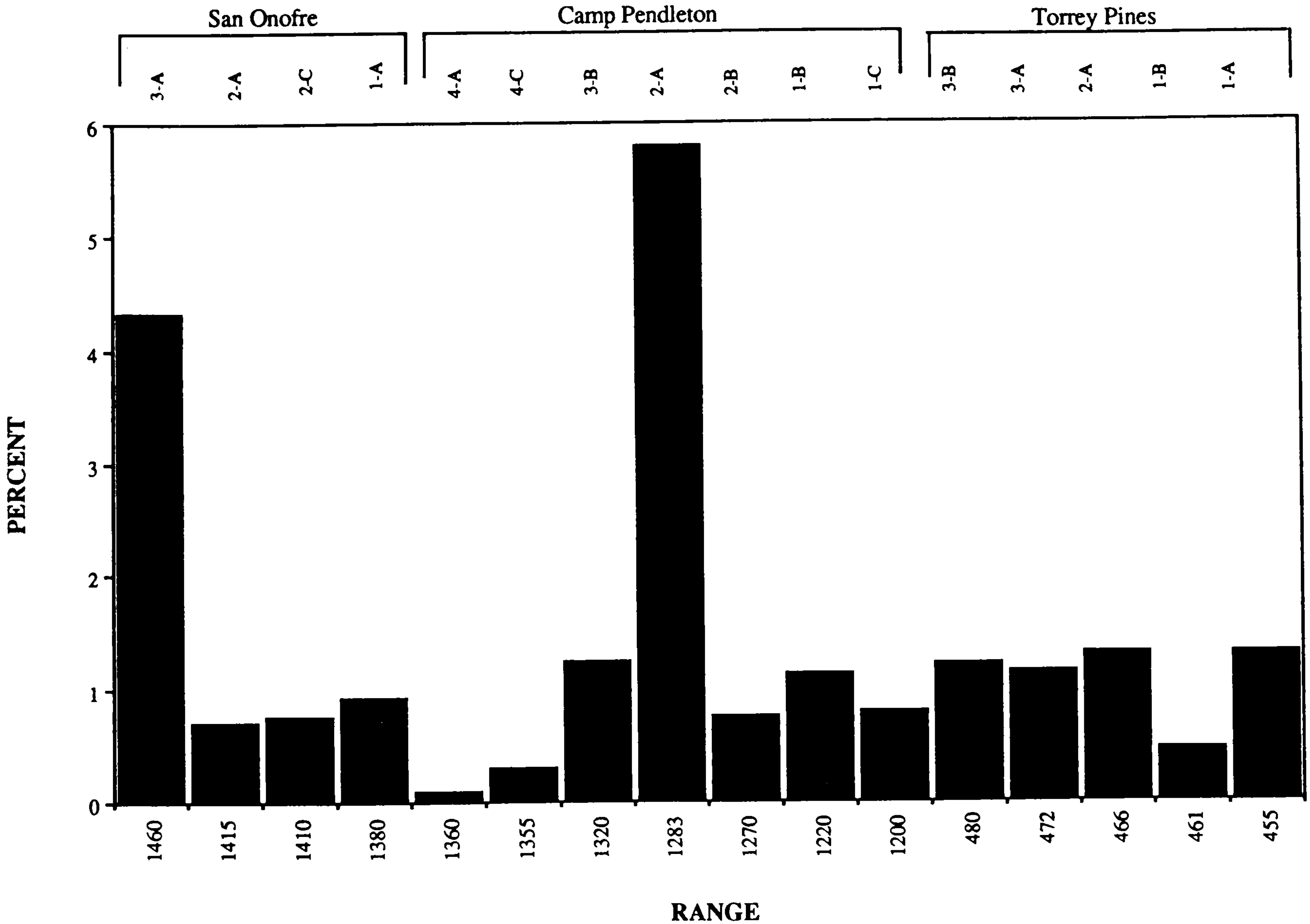


Figure 135. Percentage of garnet present in 1986 cliff samples.

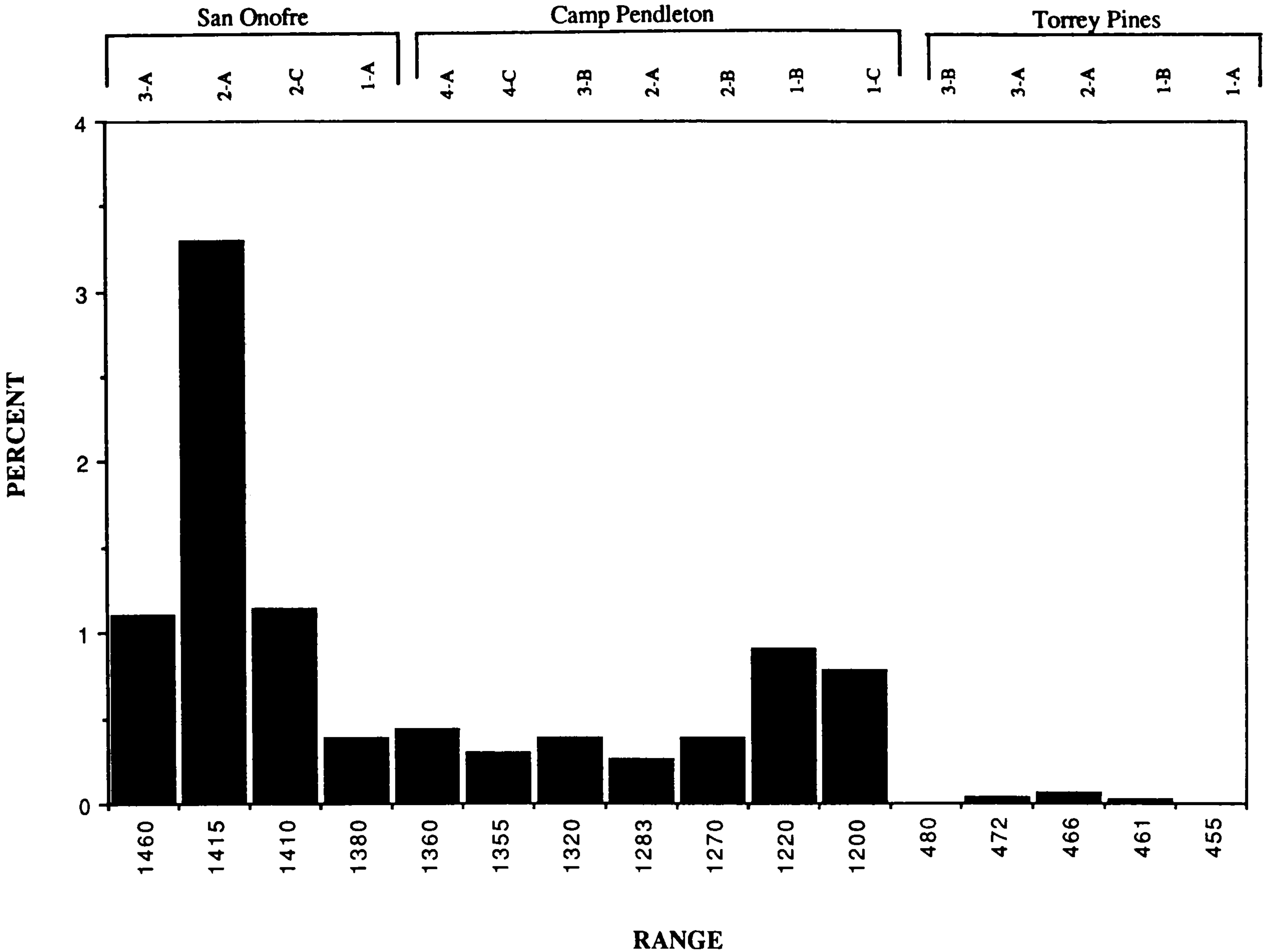


Figure 136. Percentage of glaucophane present in 1986 cliff samples.

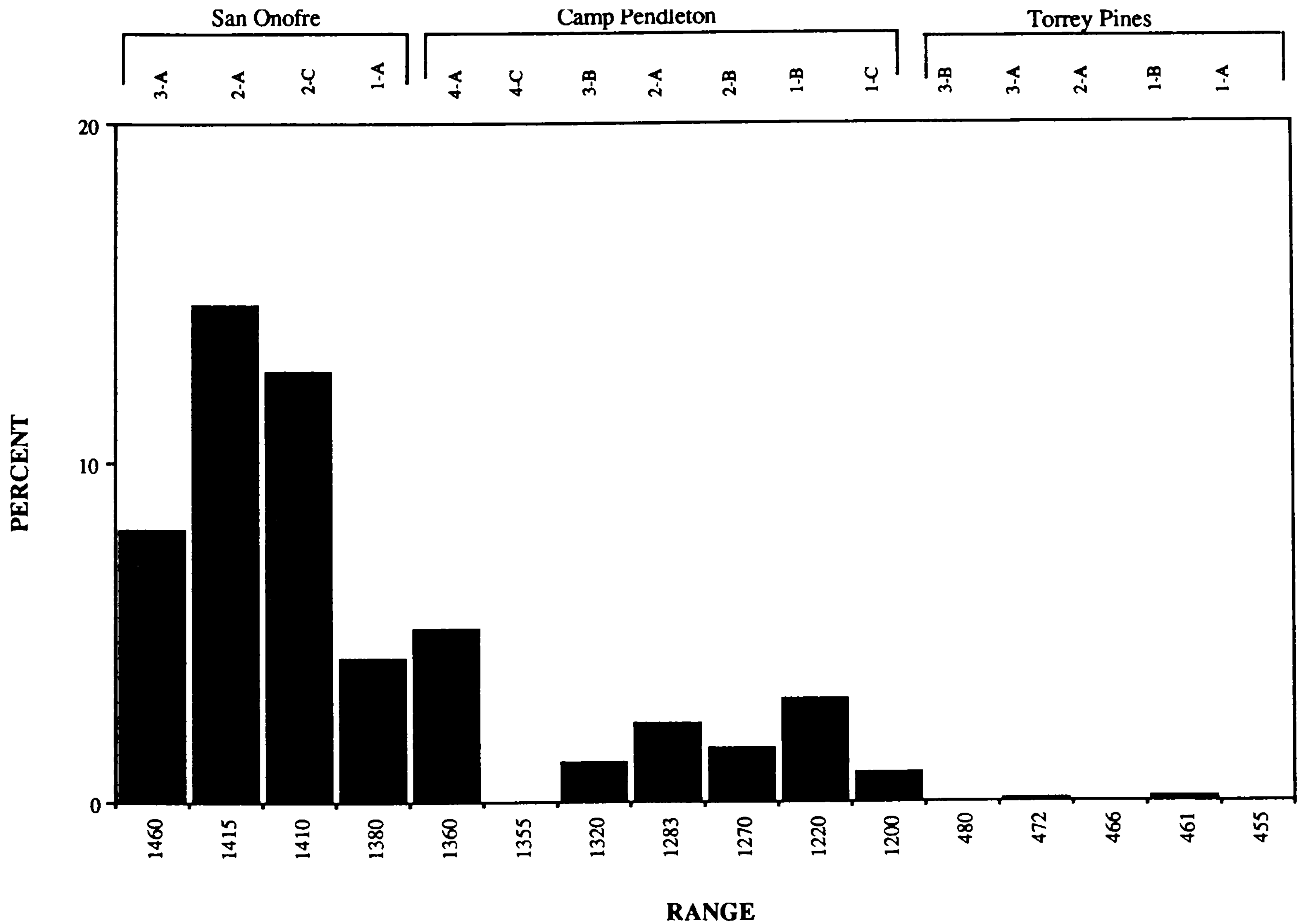


Figure 137. Percentage of glaucophane schist present in 1986 cliff samples.

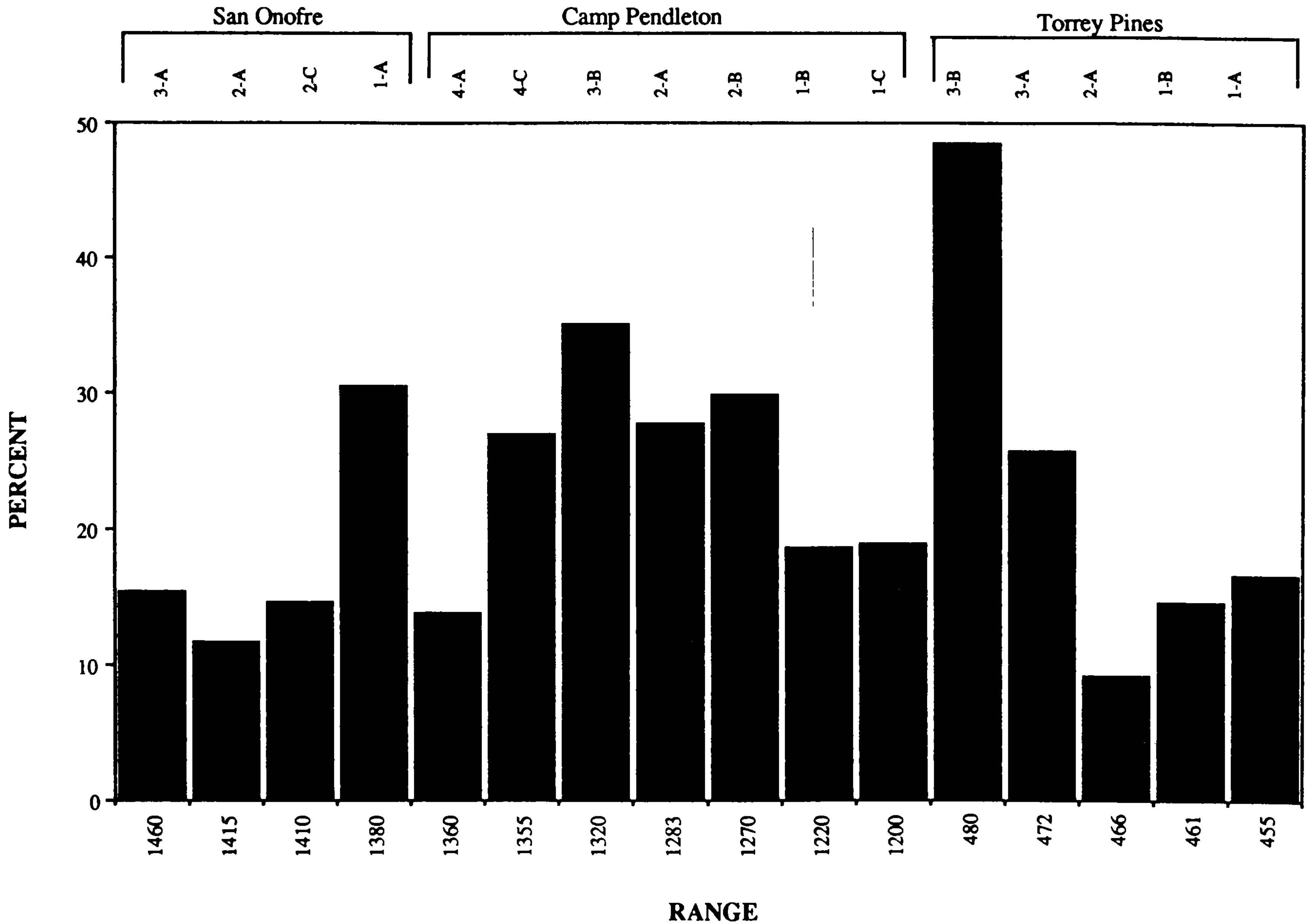


Figure 138. Percentage of hornblende present in 1986 cliff samples.

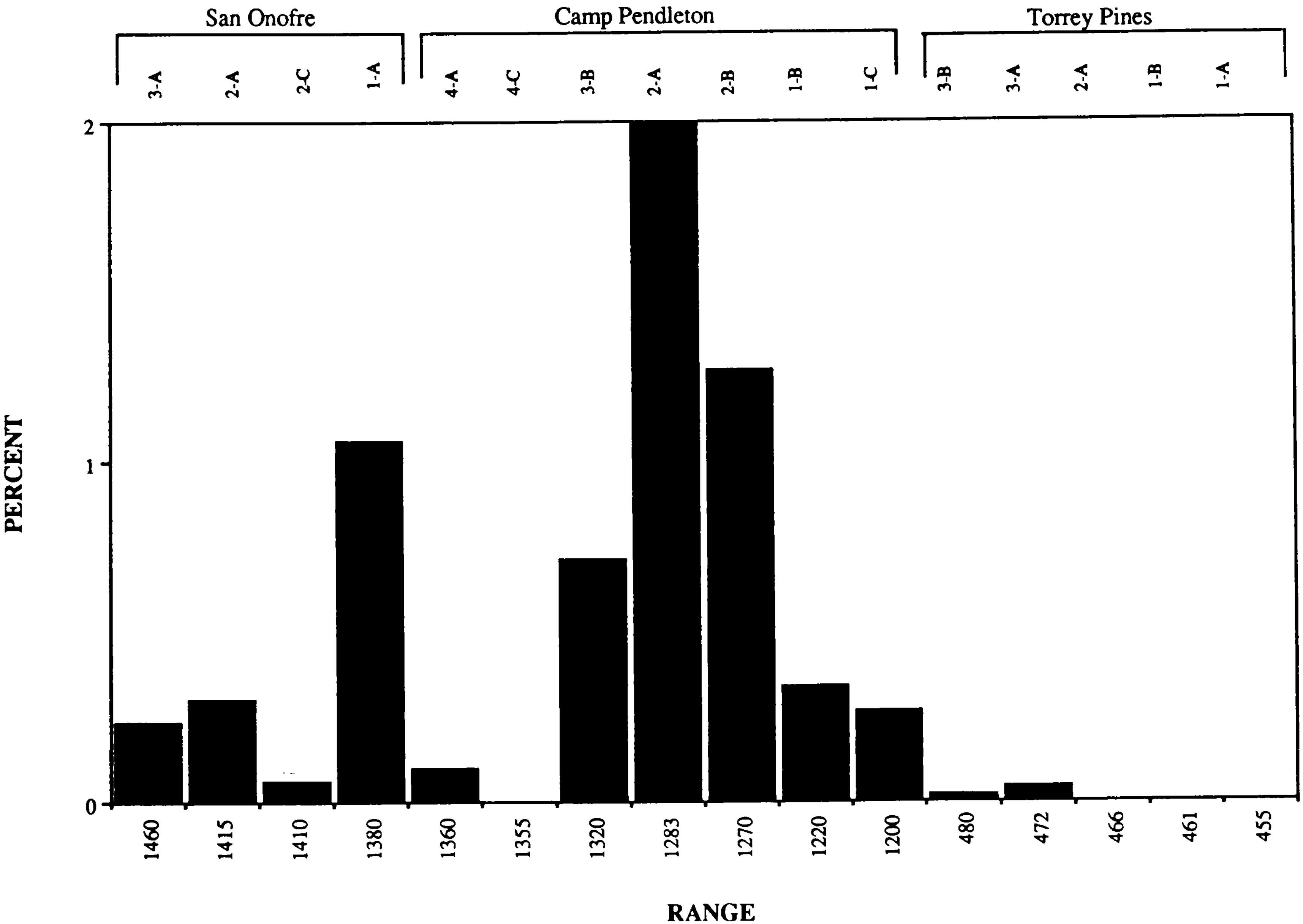


Figure 139. Percentage of hypersthene present in 1986 cliff samples.

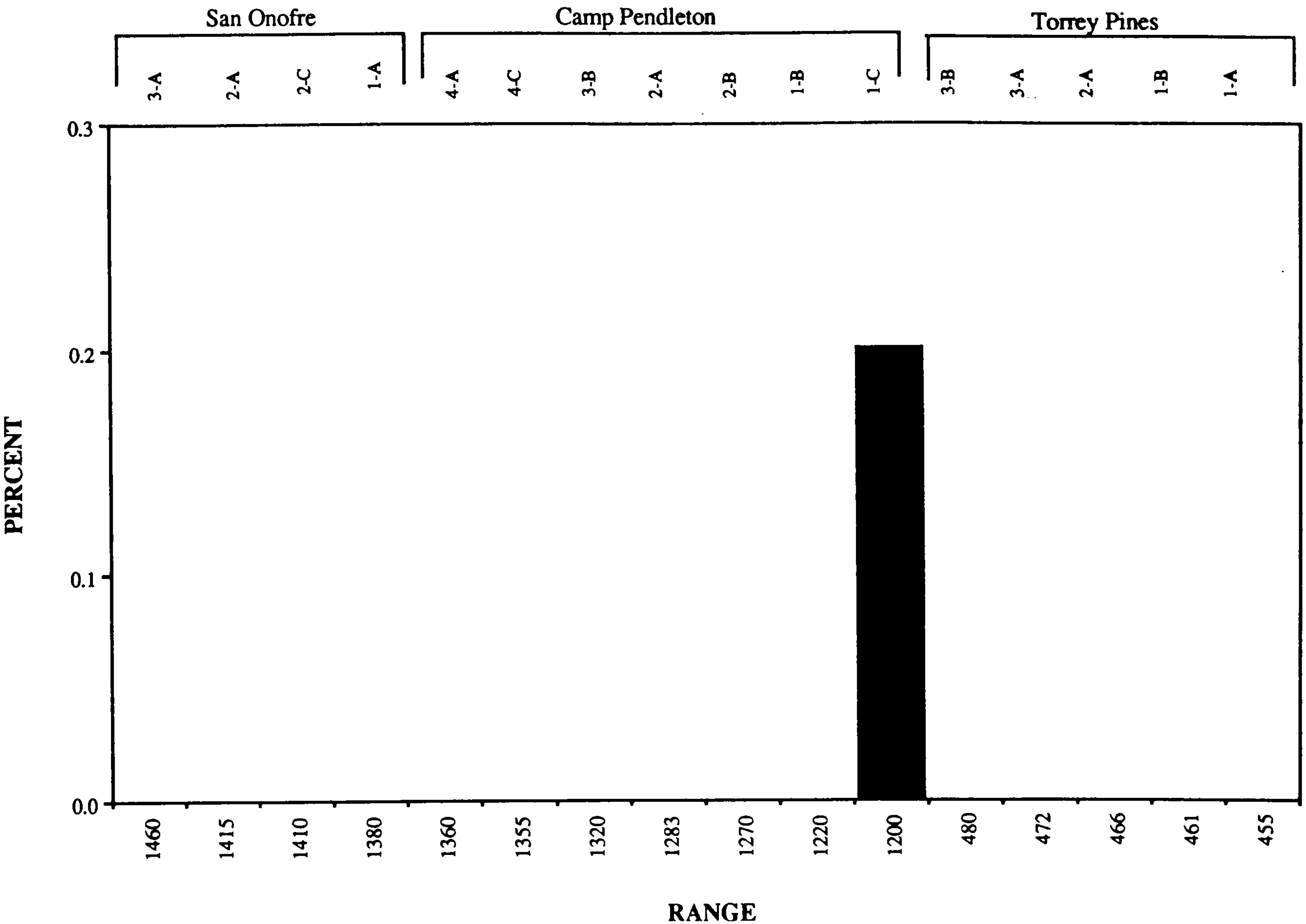


Figure 140. Percentage of olivine present in 1986 cliff samples.

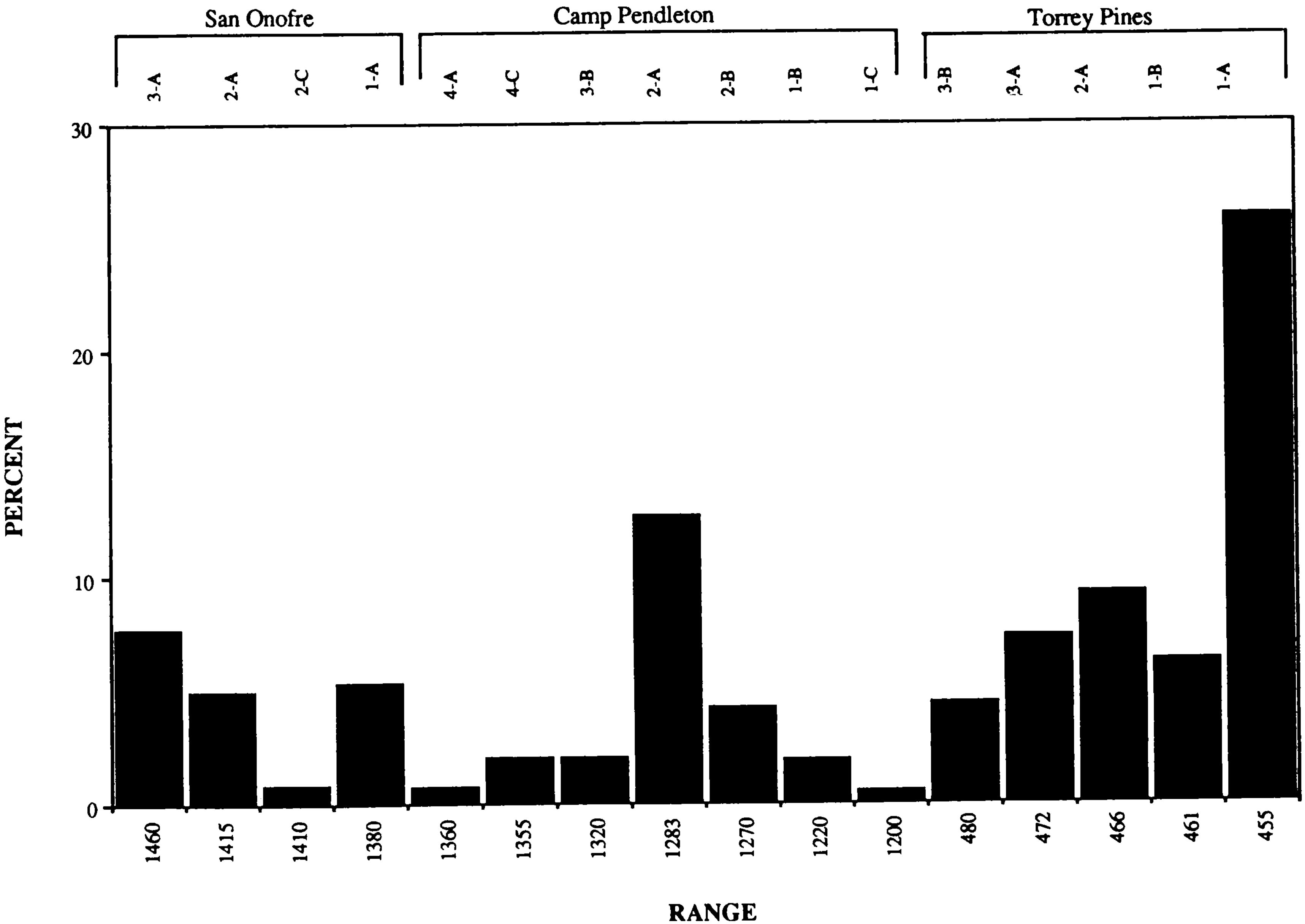


Figure 141. Percentage of opaque minerals present in 1986 cliff samples.

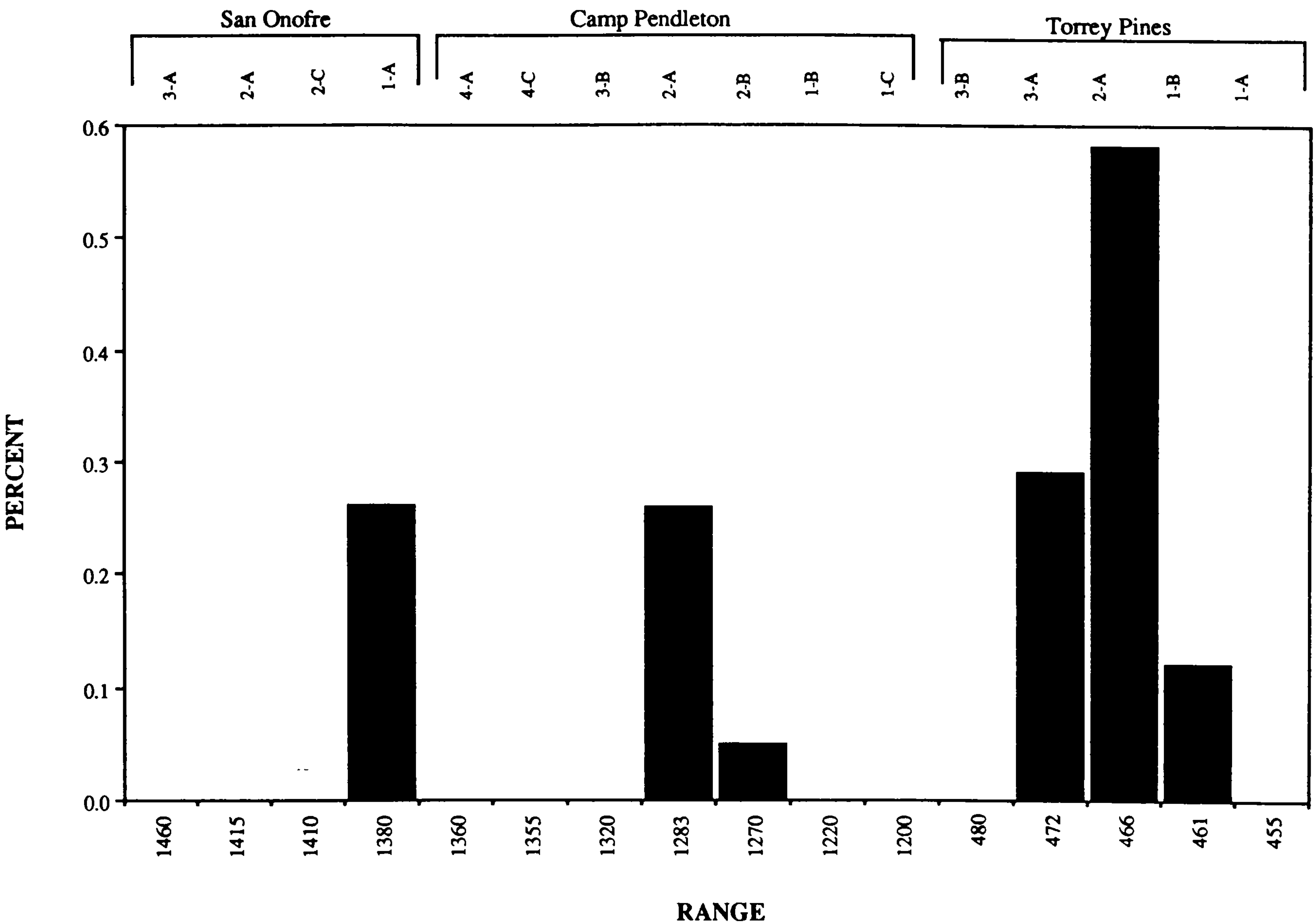


Figure 142. Percentage of piedmontite present in 1986 cliff samples.

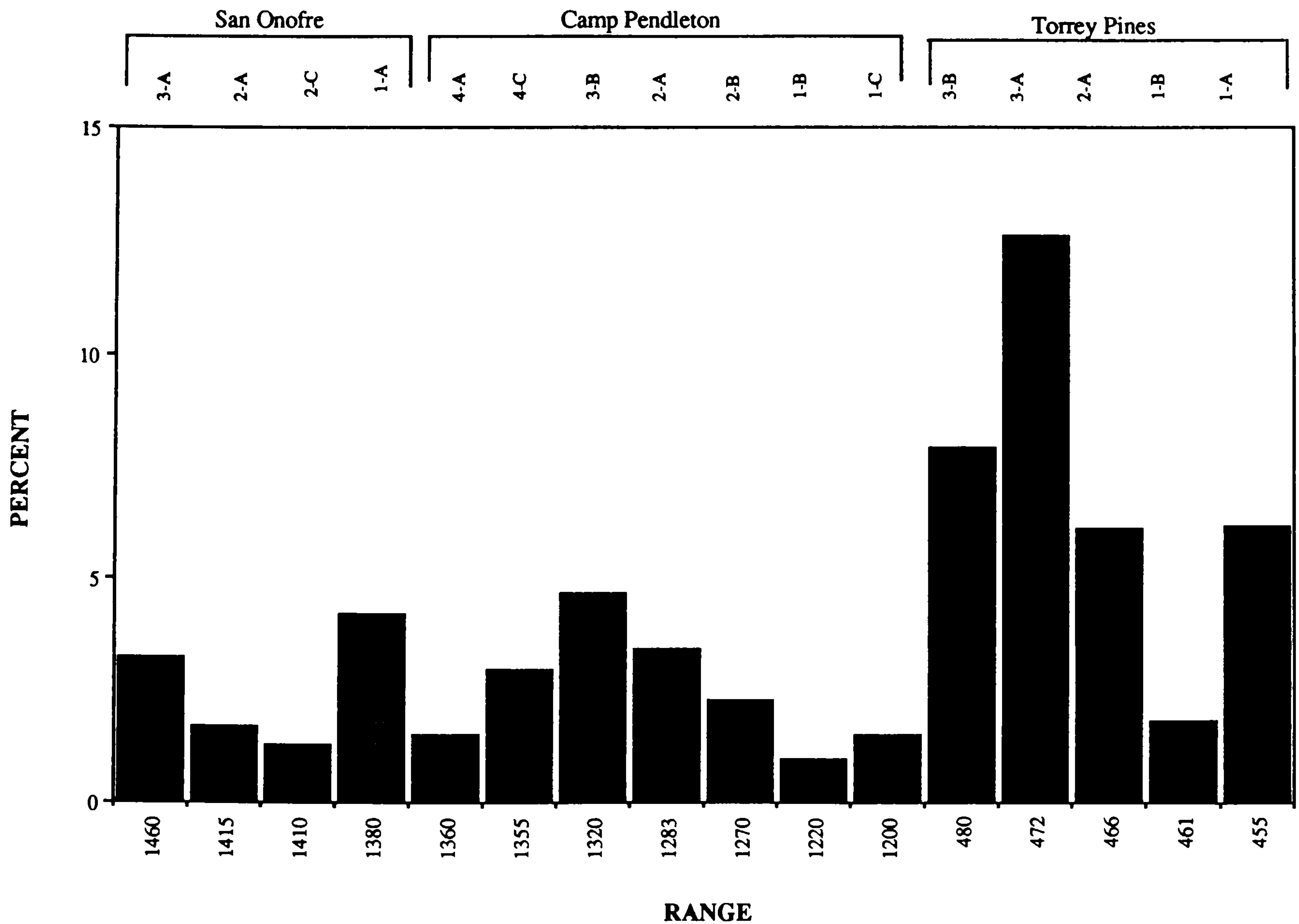


Figure 143. Percentage of sphene present in 1986 cliff samples.

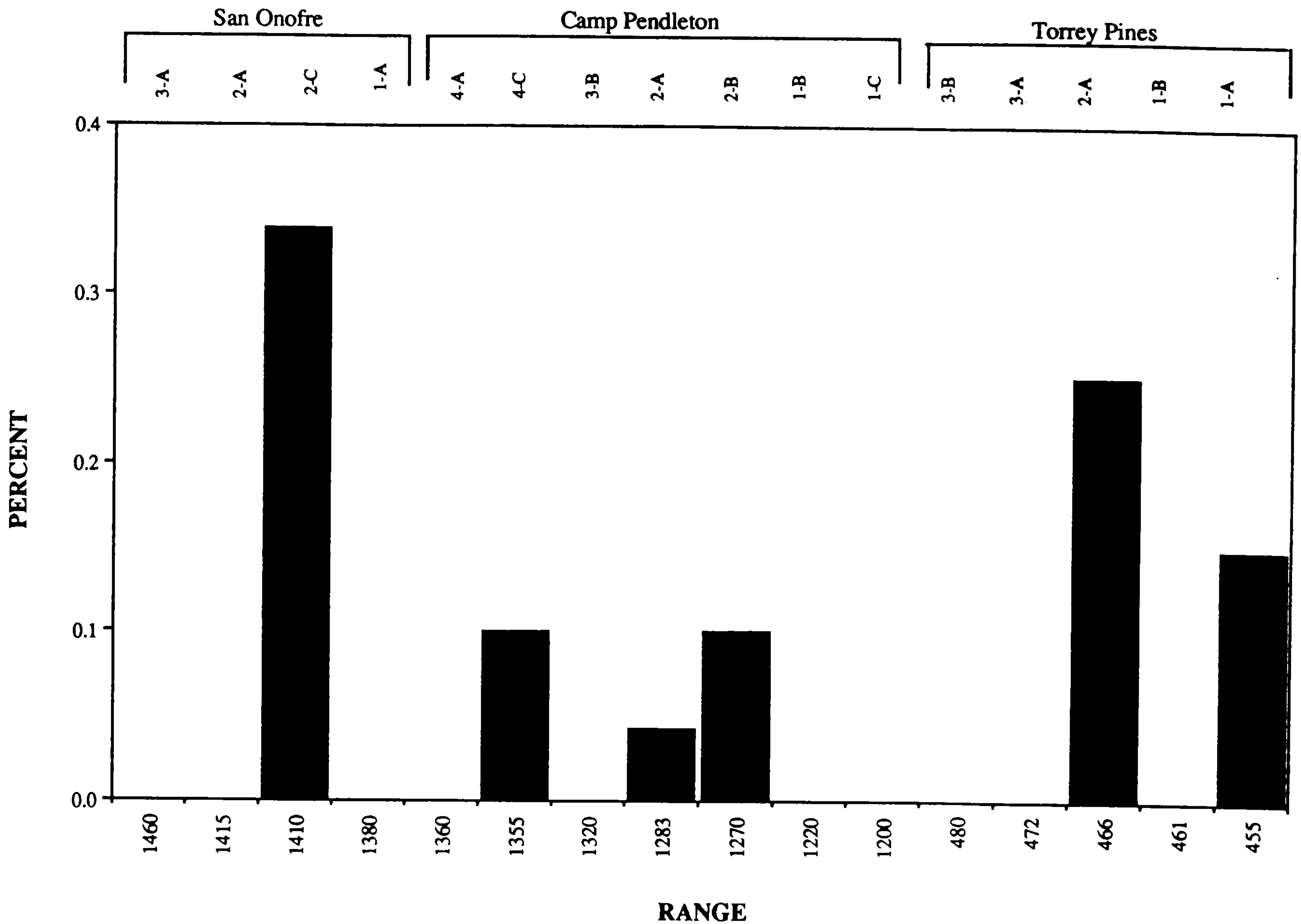


Figure 144. Percentage of tourmaline present in 1986 cliff samples.

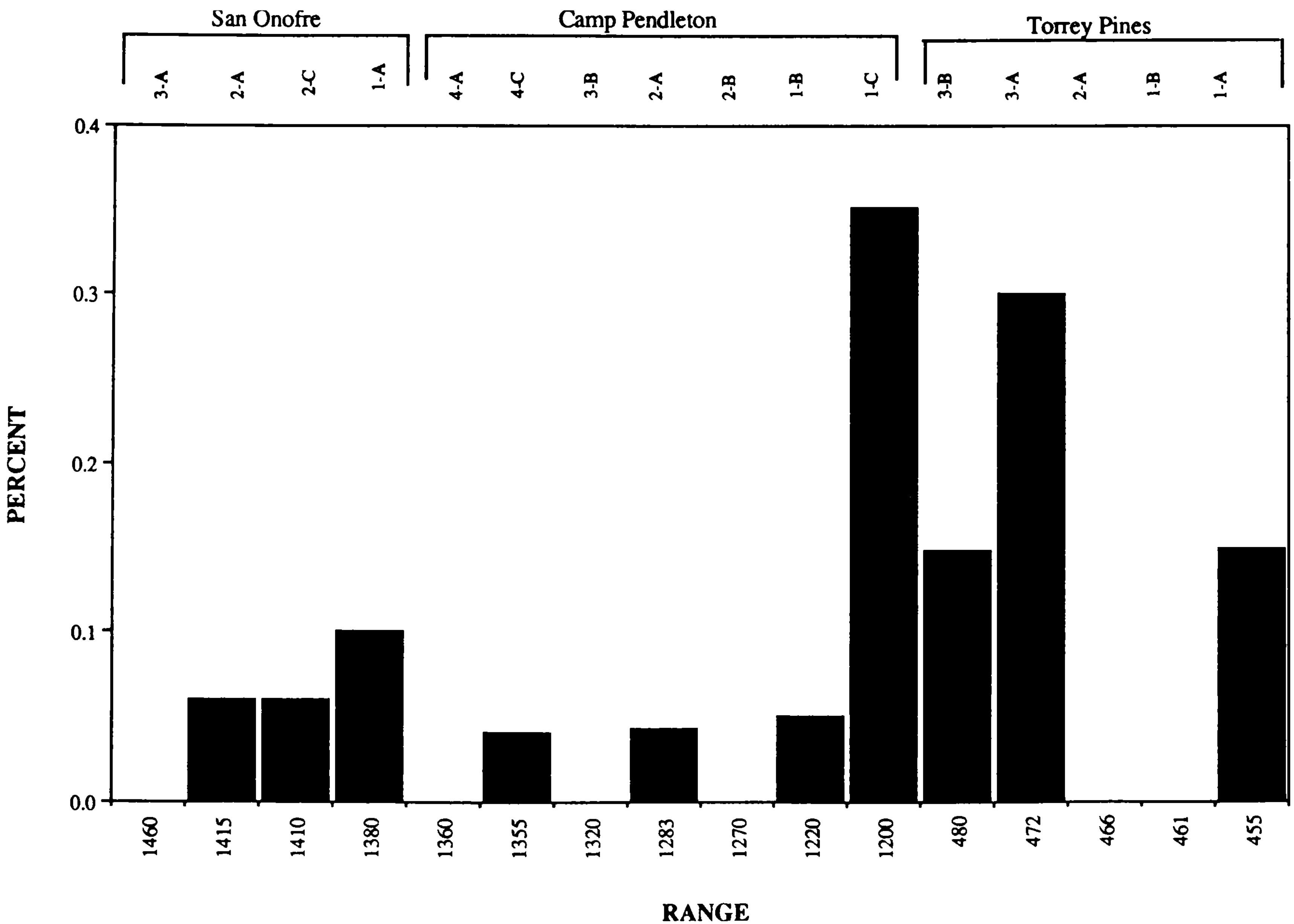


Figure 145. Percentage of zircon present in 1986 cliff samples.

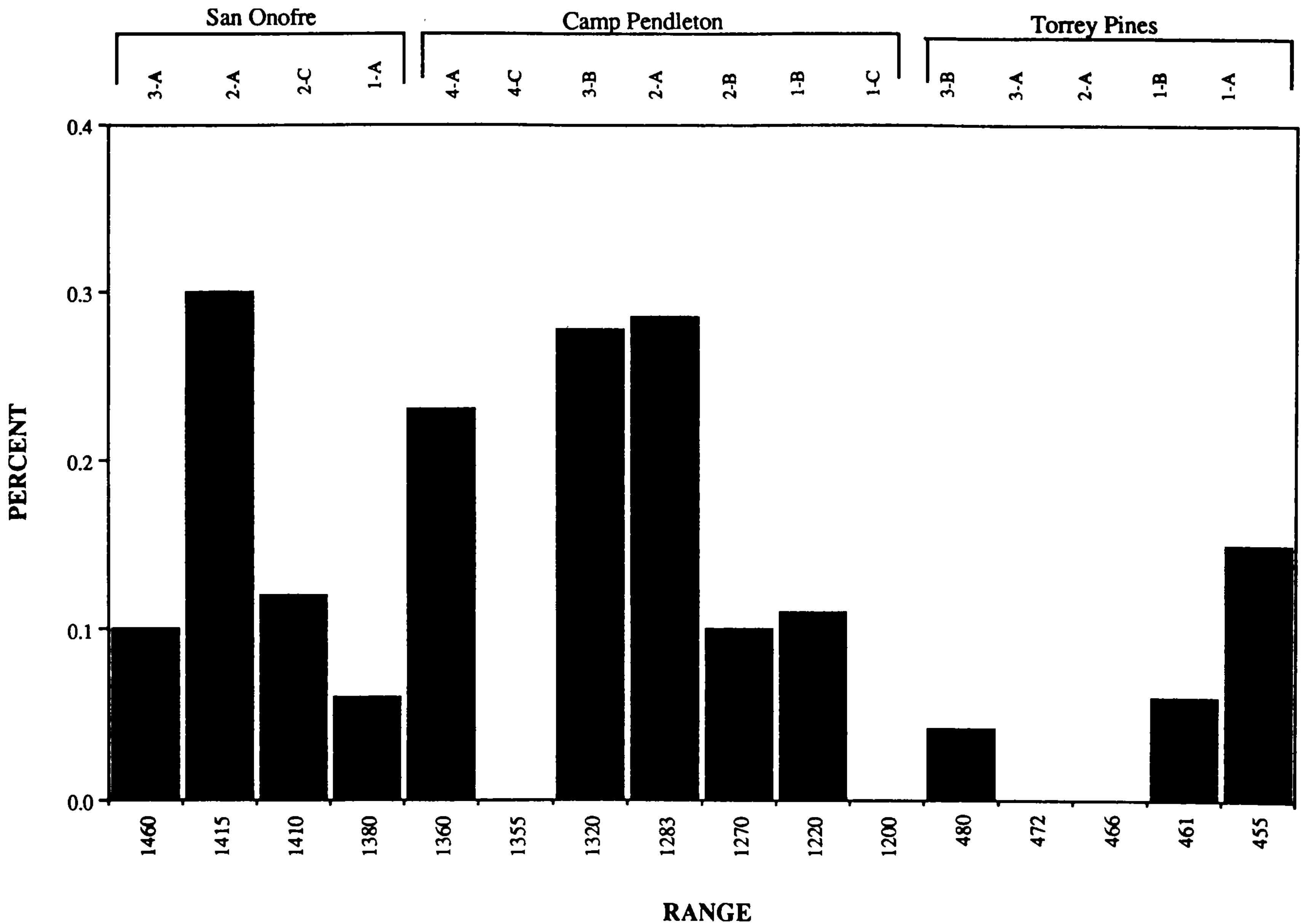


Figure 146. Percentage of zoisite present in 1986 cliff samples.

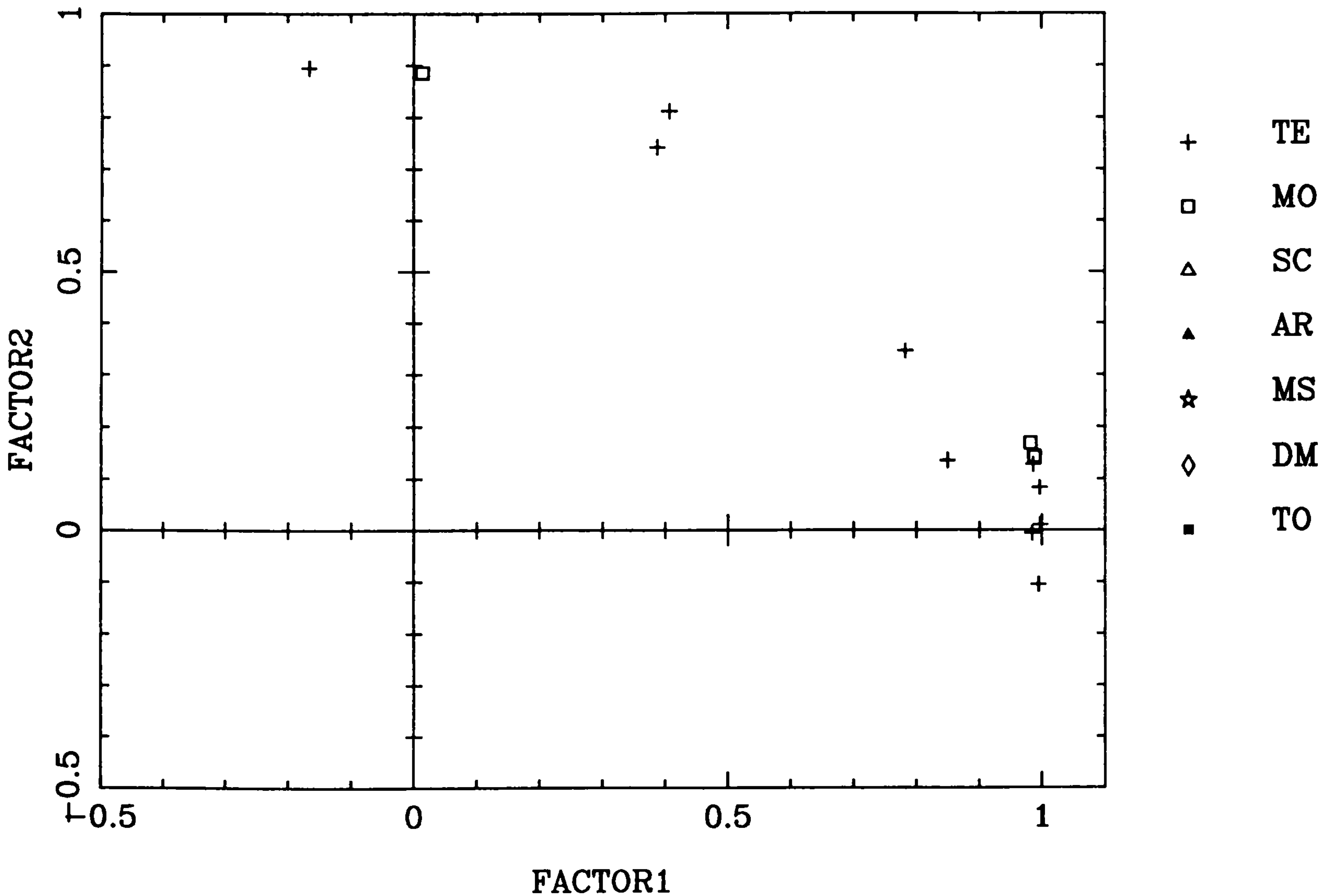


Figure 147. Results of factor analysis for total mineralogy, San Onofre area. Symbols as follows: TE - terrace deposits, MO - Monterey Formation, SC - Scripps Formation, AR - Ardnath Shale, Ms - Mount Soledad Formation, DM - Delmar Formation, TO - Torrey Sandstone.

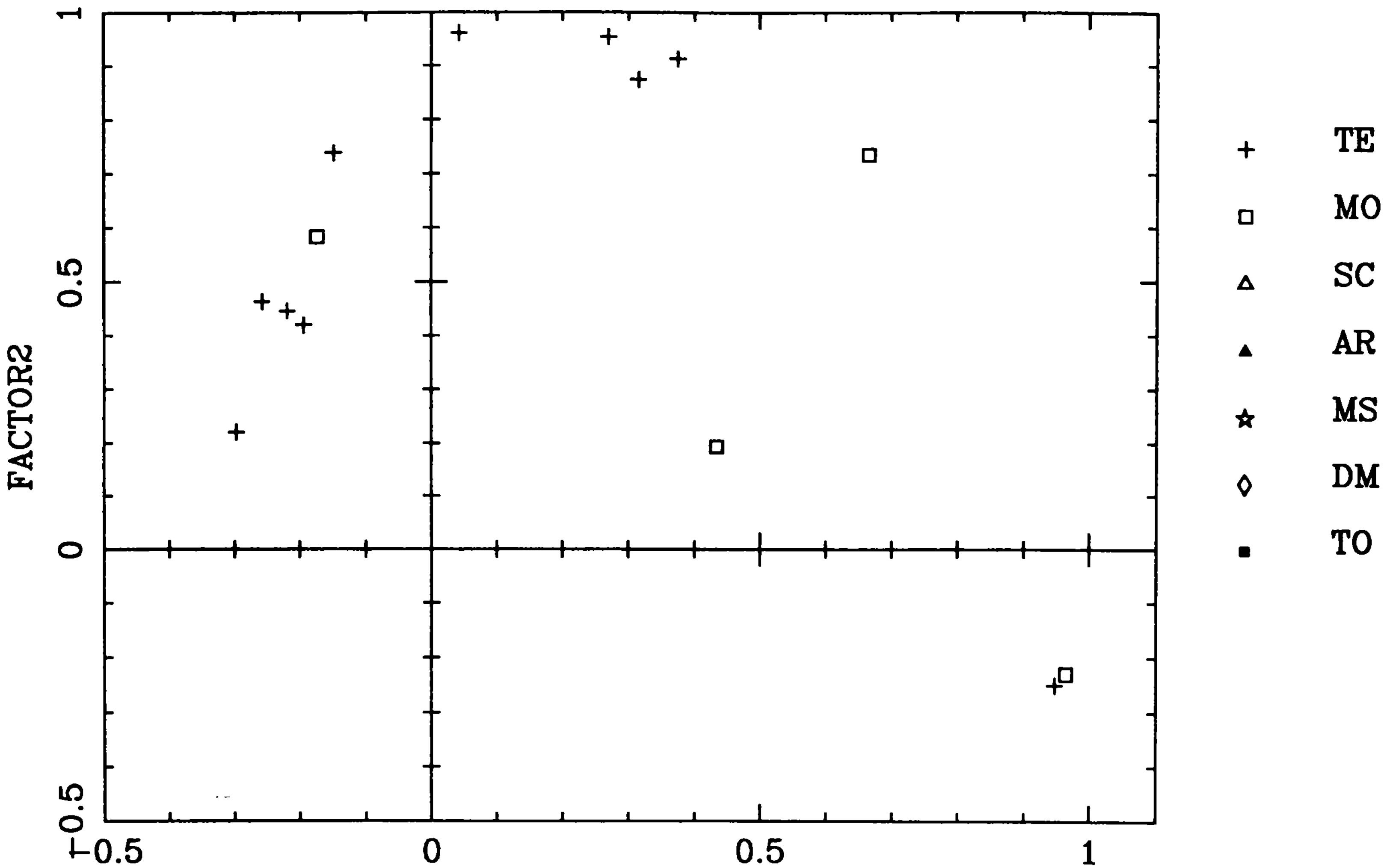


Figure 148. Results of factor analysis for heavy minerals, San Onofre area. Symbols as in Figure 138.

analysis of the total mineralogic composition of the samples showed a wide range of variability on both factors 1 and 2. Although there appears to be a linear trend between quartz and heavy minerals, with the feldspars remaining rather constant; there is too much variance for this to be considered a cluster. Factor analysis of the heavy minerals shows no distinct clusters, but the loadings suggest that factor 2 could be interpreted as a sediment source contributing hornblende.

The Camp Pendleton Area

8.20 The Camp Pendleton study area (Plate 2), a coastal segment that extends from the northern border of San Onofre State Park south to the Santa Margarita River, covers approximately 11 kilometers of the coastline on the U.S. Marine Corps Base at Camp Pendleton. There are several large canyons and streams in this region. Stratigraphic section CP-4 was measured in Horno Canyon and is the northernmost sample locality. Stratigraphic section CP-3 was measured in Dead Dog Canyon. The Las Pulgas Canyon cut by the Las Flores Creek is immediately north of sample site CP-2. Stratigraphic section CP-1, the southernmost sample locality for this region, was measured approximately 1.6 kilometers north of the Santa Margarita River.

8.21 The formations exposed in this area include the coarse, arkosic sandstone facies of the Monterey Formation (middle Miocene), which generally coarsens to the south. Lenses and channels of conglomerate containing metamorphic clasts floating in a siltstone matrix, form the overlying, reddish brown, Quaternary nonmarine and marine terrace and alluvial fan deposits, which become thicker near San Onofre. Along this coastal segment the Monterey Formation ranges in thickness from 2 to 10 meters, and becomes thicker in the south. A 30-meter exposure of Quaternary sediment at CP-4 is much thicker than the 1 meter exposed at CP-1. The Capistrano Formation is exposed at in only a few sections. Strata assigned to the Capistrano Formation represent a transition from the middle Miocene Monterey Formation to a very similar lithofacies, which was deposited during the late Miocene and early Pliocene. It remains uncertain if strata presently assigned to the Quaternary were, in fact, deposited simultaneously with the Capistrano Formation during the Pliocene (Ehlig, 1977). The contact between the Monterey Formation and the overlying unnamed Quaternary deposits is sharp and erosional, and has been correctly identified as a disconformity. Holocene colluvium caps the stratigraphic sections in some places.

8.22 The depositional environment for this area is best summarized by Stuart (1975), who describes an alluvial fan sequence prograding into a marine environment in the Camp Pendleton area during the Miocene. A widespread erosional surface occurs at the top of the La Jolla Group (Eocene). Alluvial fan deposits prograded over this surface and extended into marine environments that prevailed due to subsidence during the Miocene (Stuart, 1975). The San Onofre Breccia was the major alluvial fan deposit, which consists of characteristic metamorphic clasts derived from Catalina blueschist source terranes. The breccia was reworked from deposits in the San Onofre Mountains, and the resedimented clasts were incorporated into Quaternary terrace deposits. The sandstone facies of the Monterey Formation probably was deposited as a dense, turbidity current in a submarine fan environment (Hunt and Hawkins, 1975).

8.23 Quartz comprises more than sixty percent of each sample in the Camp Pendleton area. Similarly, plagioclase feldspar represents approximately 20 percent of each sample. Less than 15 percent of the samples are composed of heavy minerals. The enrichment in quartz and potassium feldspar is typical for the Monterey Formation in this region. Biotite is the predominant heavy mineral, comprising as much as 50 percent of the heavy mineral fraction. This large volume of biotite suggests a low-energy depositional environment. Hornblende, composite particles, and epidote are present in significant volumes along the cliffs in this region. None of these minerals show any systematic trends along the coast. Garnet occurs in most of the samples with a large amount present in stratigraphic section CP-2-A. This mineralogic assemblage represents the metamorphic influence from the San Onofre Breccia.

8.24 Samples in this region are primarily from the Monterey Formation. Factor analyses for the total mineralogy and heavy mineral suite are presented in Figures 149 and 150. There is one restricted cluster in the total mineralogy. The average composition contains 70 percent quartz, 10 percent heavy minerals, 10 percent plagioclase feldspar and 10 percent potassium feldspar. The samples are equally loaded on factor 1, which probably represents more stable minerals such as quartz. There is some spread on factor 2 which appears to be variation in relative amounts of less stable minerals such as plagioclase and heavy minerals. Factor analysis of the heavy mineral assemblage shows a broad trend, yet there is no apparent cluster of samples. Widespread distribution on both factors most likely represent the occurrence of biotite, which ranges from 4 to 90 percent. The hornblende percentage appears to be inversely proportional to biotite percentage.

The Torrey Pines Area

8.25 The Torrey Pines area (Plate 4), north of La Jolla in San Diego County, California, includes the sea cliffs from north of Scripps Institute of Oceanography pier to Bathtub Rock at Torrey Pines State Park. The coastal bluffs approximately 0.8 kilometer north of Scripps Institute along Torrey Pines Municipal Beach, locally referred to as Black's Beach, are 85 to 120 meters high. Six large canyons occur along the four kilometer segment of coast that includes all three sample sites for Torrey Pines.

8.26 Using the stratigraphic nonmenclature of Kennedy and Moore (1971), exposed units in the Torrey Pines are assigned to the La Jolla Group of middle Eocene age. Essentially, the entire La Jolla Group is represented within the Torrey Pines study area, which includes the following formation: 1) Mount Soledad Formation, 2) Delmar Formation, 3) Torrey Sandstone, 4) Ardath Shale, 5) Scripps Formation, and 6) Friars Formation. In the literature, these strata have been often referred to as members or facies of the La Jolla Formation (Hanna, 1926); therefore, it is important to recognize that the revised stratigraphic nomenclature of Kennedy and Moore (1971) is being used

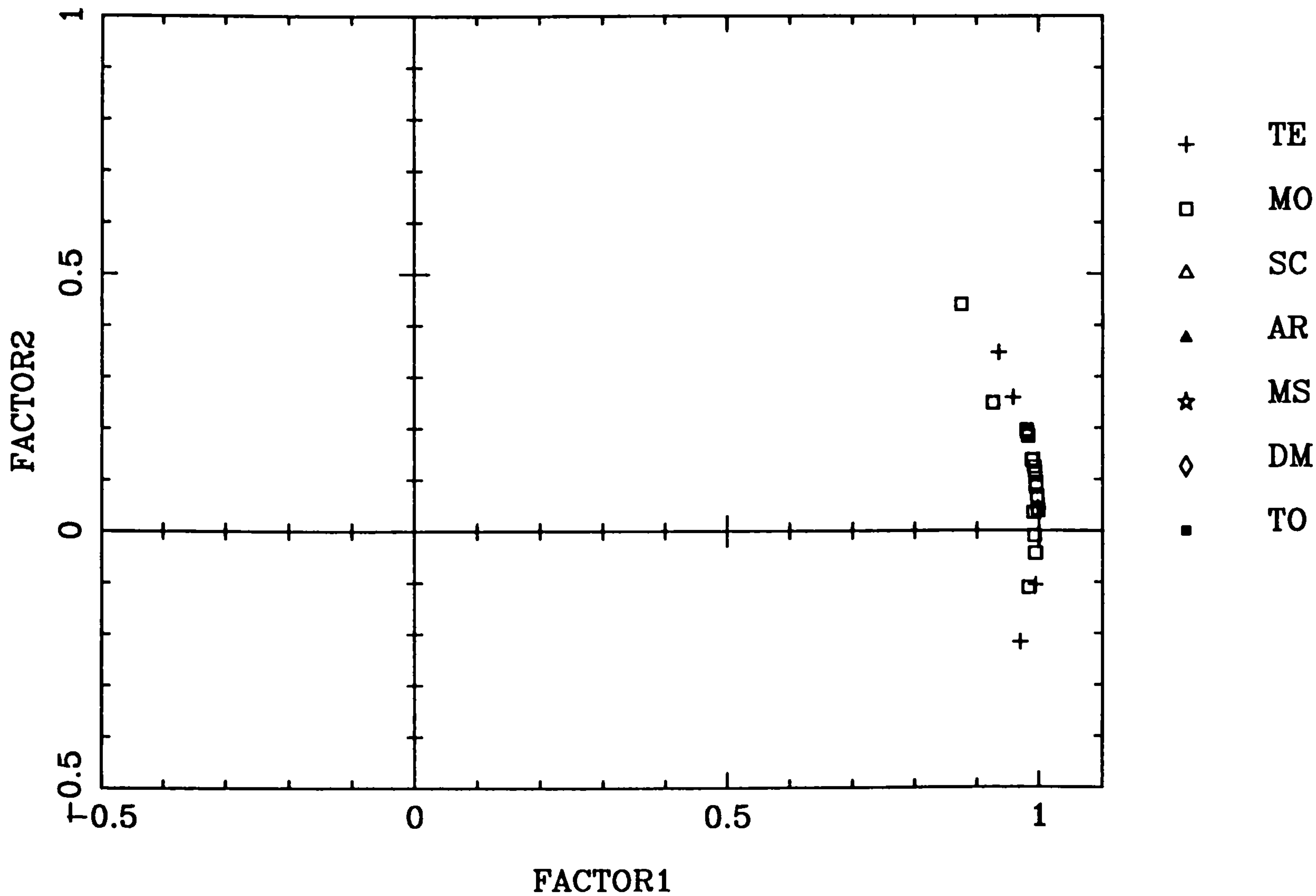


Figure 149. Results of factor analysis for total minealogy, Camp Pendleton area. Symbols as in Figure 138.

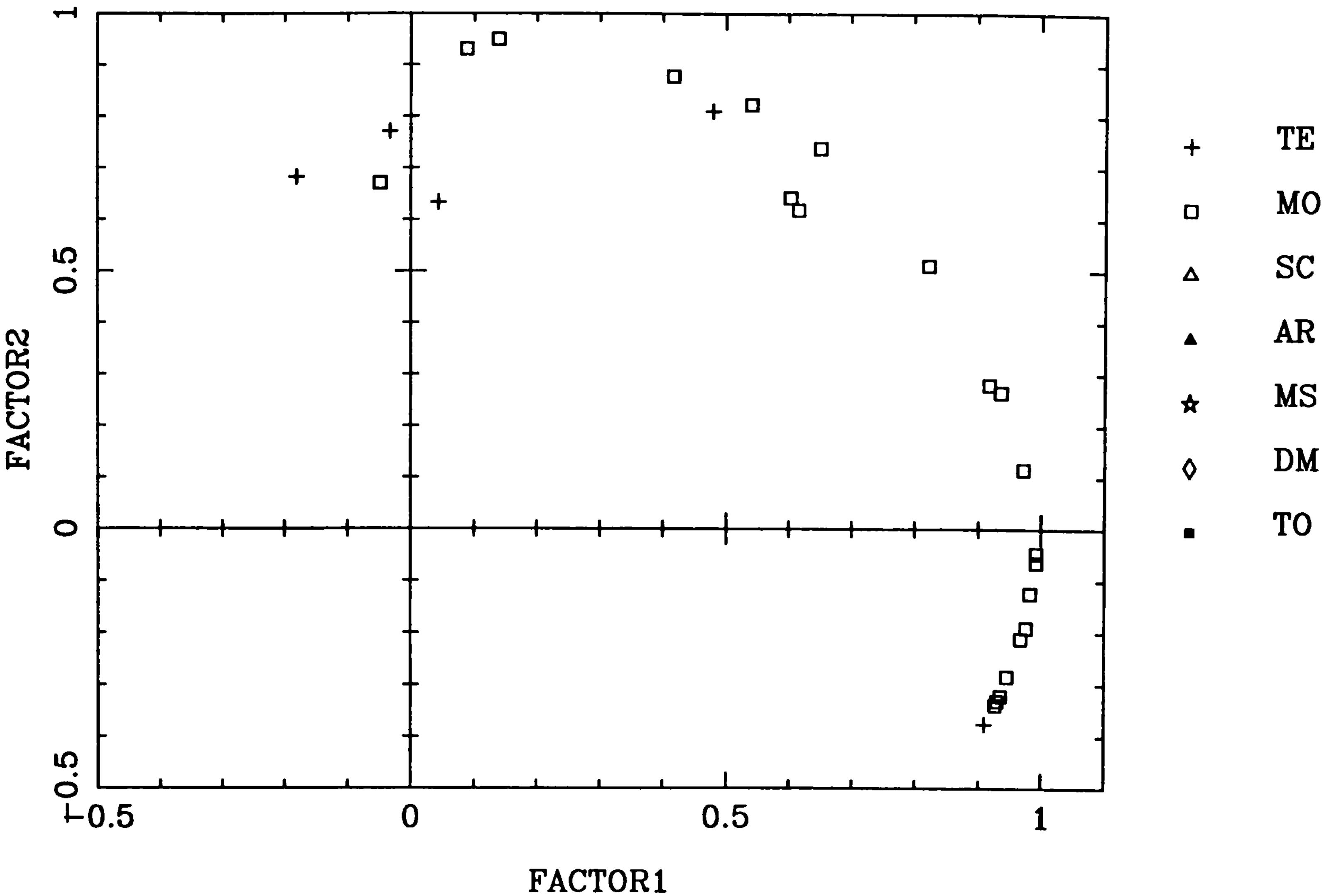


Figure 150. Results of factor analysis for total mineralogy, Camp Pendleton area. Symbols as in Figure 138.

in this report. Strata chiefly exposed in the field area are the Scripps Formation, Ardath Shale Formation, and the Torrey Sandstone Formation. The Scripps Formation, an interbedded sandstone and conglomerate, conformably overlies and interfingers with the Ardath Shale, an olive-gray, richly microfossiliferous, silty shale, which contains thin sand layers, concretions and molluscan fossils (Bukry and Kennedy, 1969). The Torrey Sandstone interfingers with the Ardath Shale as a transgressive facies (Kennedy and Moore, 1971), and is a tan, arkosic sandstone with large-scale cross-bedding. This facies has been interpreted as a barrier beach and bar deposit (Lohmar et al., 1979). The Mount Soledad Formation crops out at the base of Indian Trail Canyon, sample site 3, as a grayish-red rhyolite-bearing conglomerate. Only sections that were measured north of the glider port included the Delmar Formation, which is a dusky-yellowish-green sandy siltstone interbedded with sandstone. The type section has several layers of Ostreaidriaensis (Hanna, 1926) indicative of a lagoonal environment. These fossil-bearing strata were not found in the field area. The uppermost formation of the La Jolla Group, the Friars Formation, conformably overlies the Scripps Formation, but it is not found in the field area. This nonmarine Formation includes yellowish-gray sandstone with several interbedded siltstone beds (Lohmar and others, 1979).

8.27 Sample site 3, includes a pebbly sandstone as the basal unit with an uneven erosional surface separating the deeper-water facies of the Ardath Shale from the shelf deposits of the Delmar Formation and Torrey Sandstone. The presence of this erosional surface suggests two distinct cycles of deposition within the Eocene Epoch. The Ardath Shale, Scripps Formation, Torrey Sandstone, and the Delmar Formation were deposited in the San Diego Embayment as a wedge of clastic sediment representing littoral, slope, and outer shelf environments (Kennedy and Moore, 1971). The strata exposed in the seacliffs of the Torrey Pines area are best interpreted as a cross-section through an Eocene submarine canyon and associated submarine fan lobes (Lohmar and others, 1979). In as much as the pebbly sandstone facies of the Torrey Sandstone lies above an erosional surface with rip-up clasts and has features of a resedimented deposit, it has been interpreted as the channelized upper slope of an Eocene submarine canyon (Lohmar and others, 1979). Evidence for a resedimented deposit include 1) erosion of underlying bedrock by sandstone injection, 2) large, isolated, suspended blocks of siltstone, 3) thick, massive sandstone overlain by planar, wavy laminated sandstone, and 4) pillar convolutions and dewatering structures due to rapid deposition. The Torrey Sandstone and Delmar Formation, underlying the bathyl Ardath Shale, have channels filled with fine-grained sediment, which is another indicator for submarine slope deposition (Walker, 1975). This association of mudstone channel-fill deposits and resedimented pebbly sandstone adjacent to the shelf edge deposits can be explained by the occurrence of a submarine canyon adjacent to the ancient shoreline (Walker, 1975).

8.28 A systematic downcoast trend of decreasing quartz and increasing heavy minerals is present in the Torrey Pines region (Figure 127). A major increase in plagioclase occurs downcoast, but it does not have a systematic trend. Biotite is the dominant heavy mineral, and it increases significantly downcoast. However, hornblende decreases dramatically downcoast within the coastal cliffs. Althouth epidote and composite particles remain much the same along there is a subtle change in dominant source lithology from the metamorphic terrane in the northern segment to an acid-plutonic source terrane in the southern segment. the coast. Sphene, a prevalent accessory mineral in this region, originates from acid-plutonic rocks. Torrey Pines has the greatest volume of opaques throughout the seacliffs, and there is a significant peak of opaques near the U.S.-Mexico International border. All the samples from the Torrey Pines area are from the Torrey Sandstone and Scripps Formation.

8.29 Factor analysis was performed for the total mineral composition and the heavy mineral fraction using two factors (Figures 151 and 152). The Torrey Sandstone and the Scripps Formation in the Torrey Pines region have a similar cluster distribution for the factor analysis of the total mineral composition. Both have relatively high loadings on factor 1, which may represent the percentage of stable minerals such as quartz. Despite the relatively good cluster of samples, the results of the factor analyses does not indicate significant mineralogic differences between samples from Scripps Formation and those from the Torrey Sandstone.

8.30 In terms of total mineralogy, almost all of the samples show considerable similarity for the region (Figure 153). The heavy mineral assemblage for the regional data indicates some separation by formation (Figure 154). Samples from the Quaternary terrace deposits and the Monterey Formation are broadly clustered with a low loading on factor 1. Samples from the Scripps Formation, however, are represented as a small, distinct cluster having high loadings for factor 1 and low values for factor 2. Analyses from the Monterey Formation samples span the entire factor plot, reflecting the high variance associated with heavy mineral content.

Summary of Mineralogic Trends

8.31 There is a high percentage of epidote and glaucophane schist in the San Onofre cliffs as compared with those in the Camp Pendleton and Torrey Pines areas. There is twice as much epidote (nearly 50 percent) in the northernmost San Onofre coastal cliffs as compared with the samples with the most epidote from the combined Camp Pendleton-Torrey Pines cliff segment. Three of the four samples from San Onofre contain more epidote than the sample with the most epidote from the combined Camp Pendleton-Torrey Pines cliff segment (Figure 133). Furthermore, the percentages for glaucophane and glaucophane schist are much greater than those from the Camp Pendleton area, and these minerals are virtually absent within the bluffs at Torrey Pines. The high percentages of epidote, glaucophane and glaucophane schist in the San Onofre and Camp Pendleton areas reflect ultimate clast derivation from a metamorphic source terrane. The observed clasts were reworked from the San Onofre Breccia, which was, in turn, ultimately derived from the Catalina Blueschist Terrane. The San Onofre Breccia crops out from an area east of Dana Point southward almost to Oceanside. Likewise, minor quantities of actinolite (less than 0.5 percent) occur in almost every sample within the San Onofre and Camp Pendleton sea cliffs, but this mineral is absent in the Torrey Pines area.

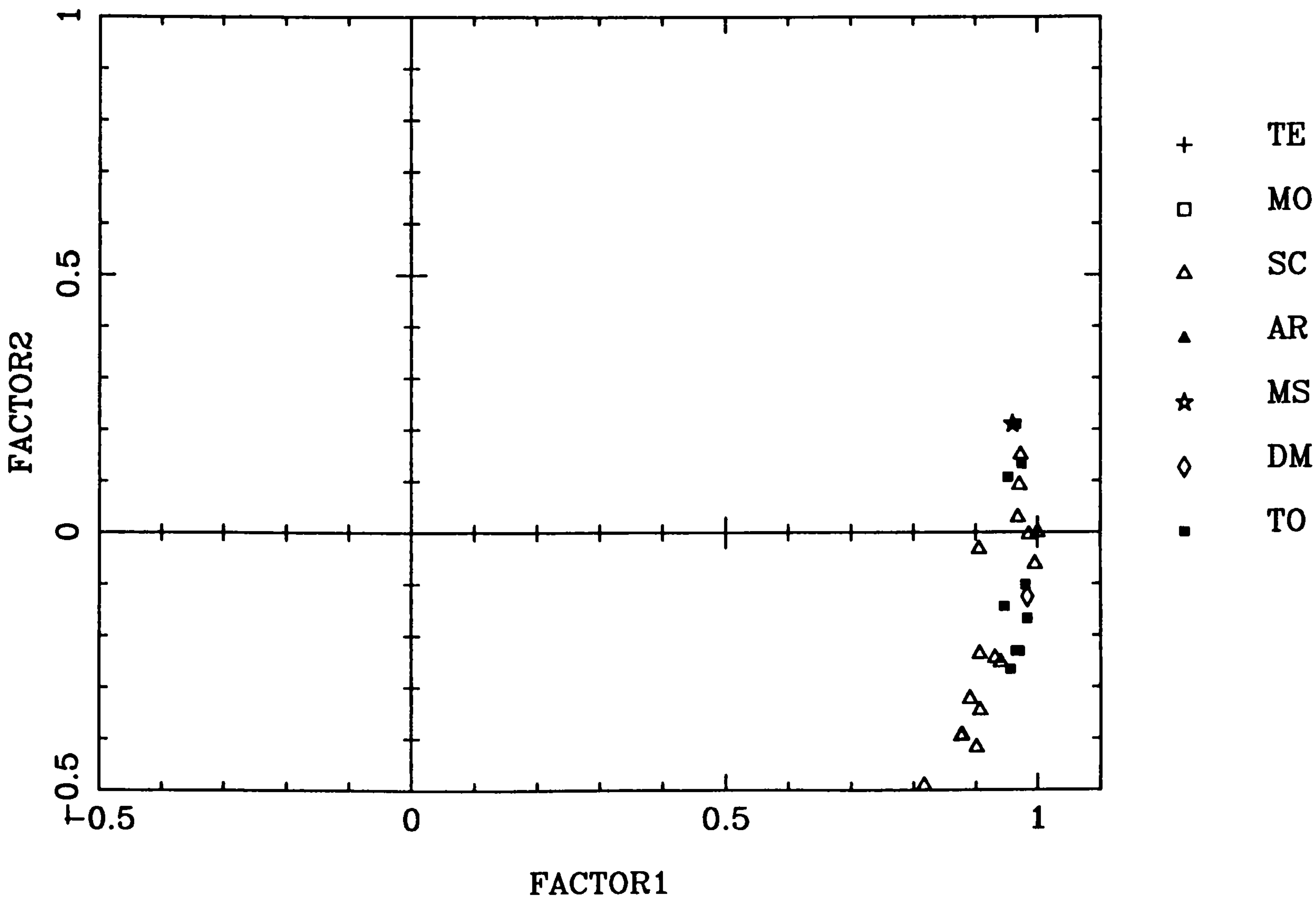


Figure 151. Results of factor analysis for total mineralogy, Torrey Pines area. Symbols as in Figure 138.

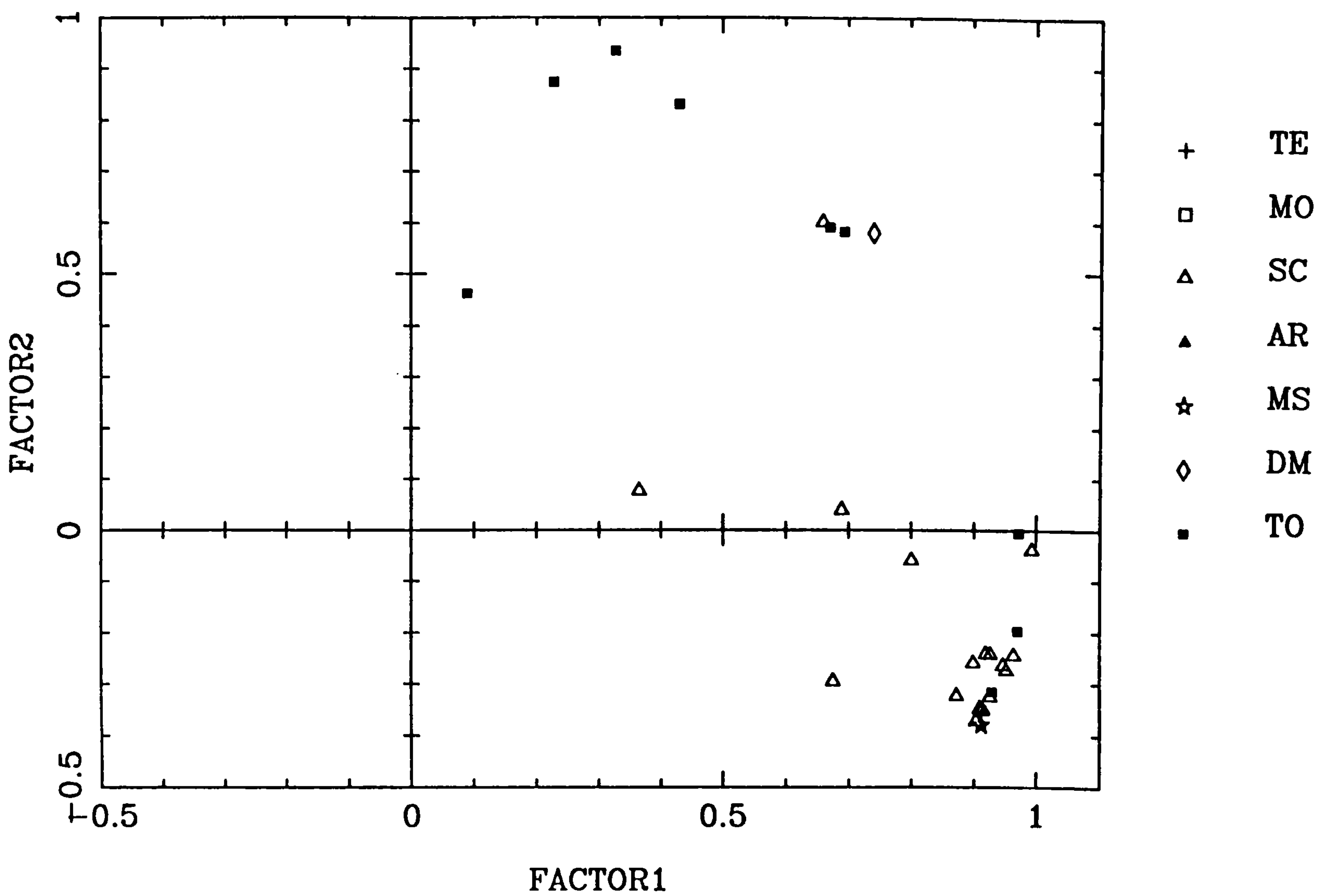


Figure 152. Results of factor analysis for heavy minerals, Torrey Pines area. Symbols as in Figure 138.

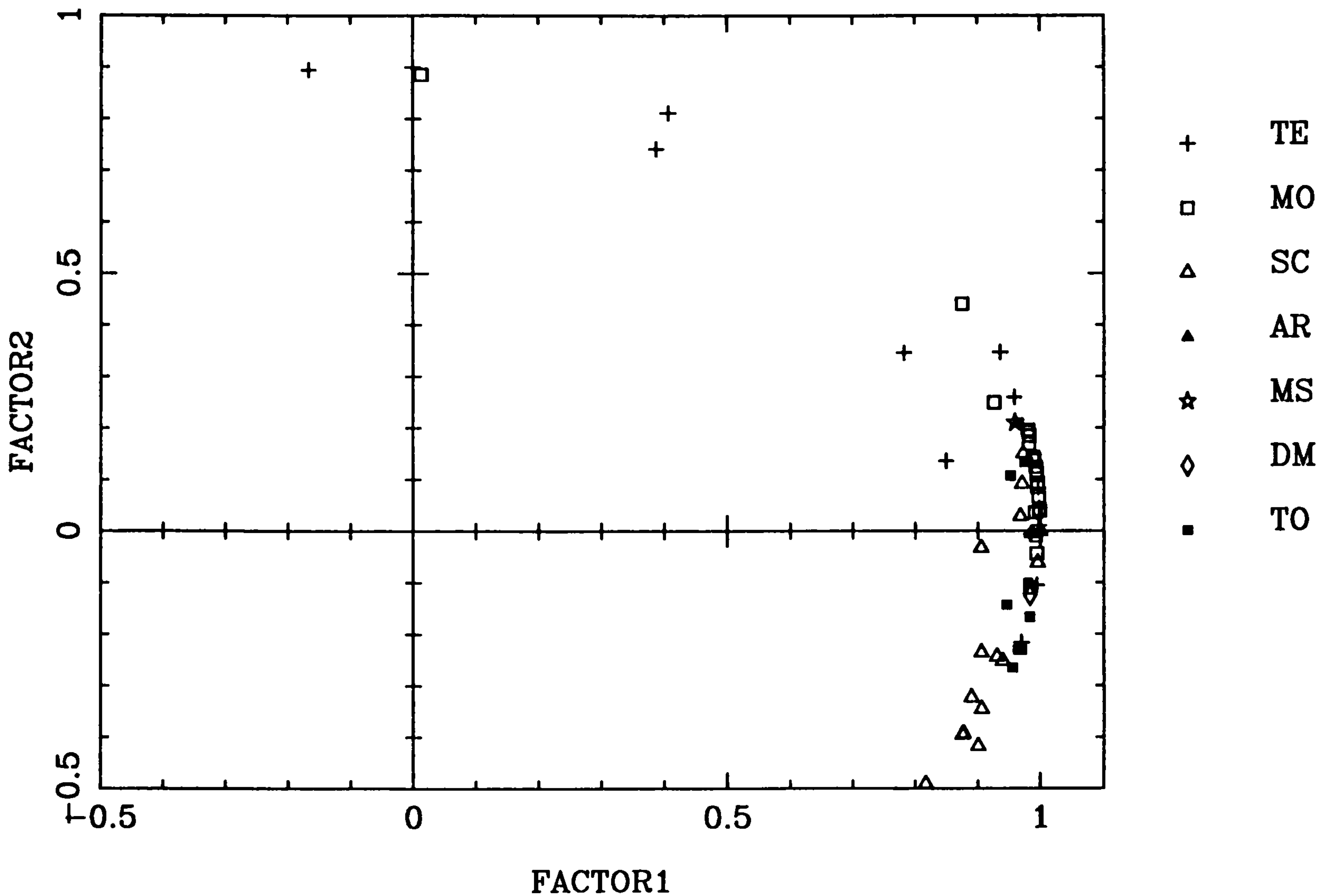


Figure 153. Results of factor analysis for total mineralogy for San Onofre, Camp Pendleton, and Torrey Pines area. Symbols as in Figure 138.

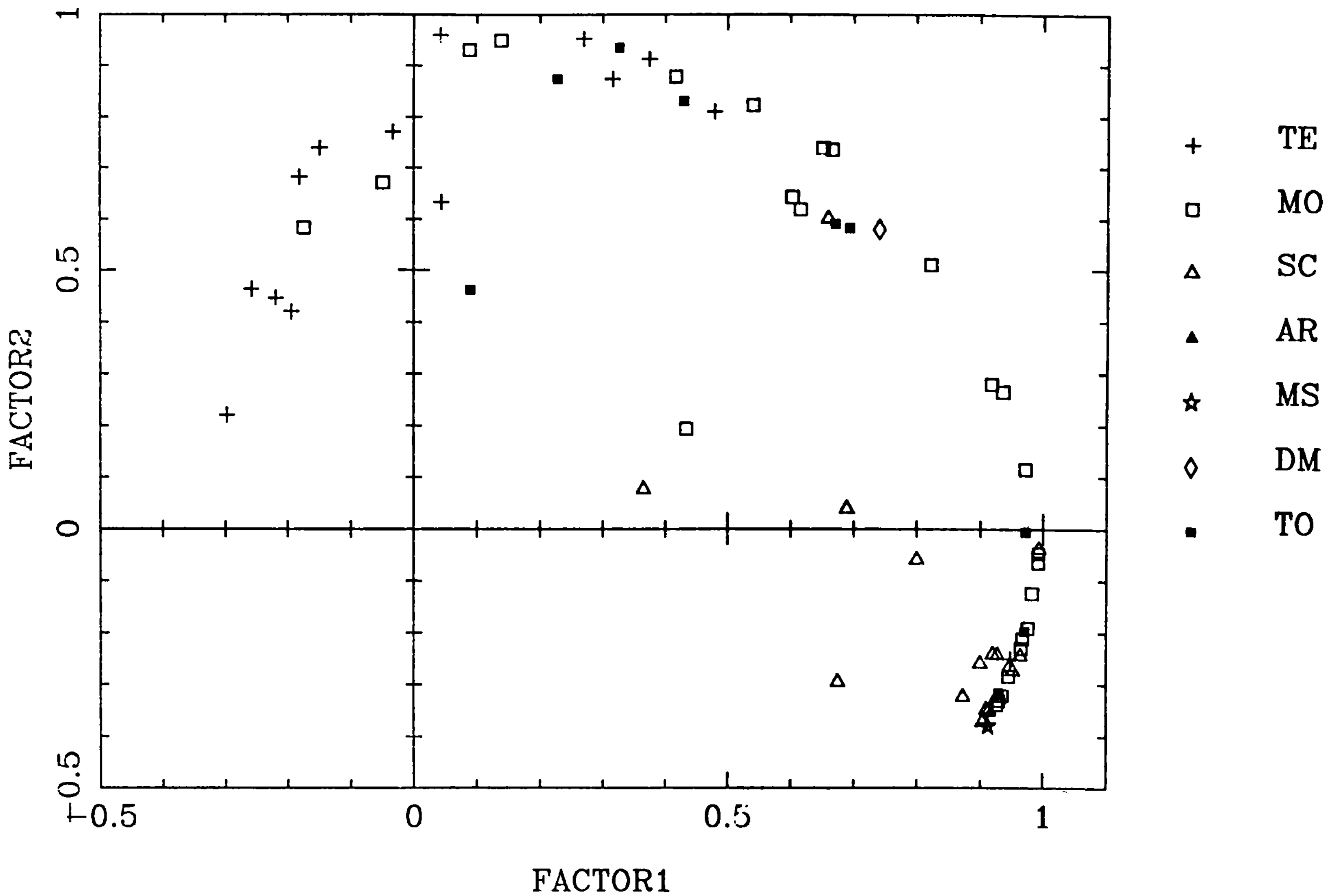


Figure 154. Results of factor analysis for heavy minerals for San Onofre, Camp Pendleton, and Torrey Pines area. Symbols as in Figure 138.

8.32 The percentage of sphene and opaque minerals in the samples from Torrey Pines is much higher than those from San Onofre and Camp Pendleton. Sphene comprises less than five percent of the heavy mineral fraction in all of the cliff samples from San Onofre and Camp Pendleton (Figure 143). The heavy mineral fraction from Torrey Pines sample site (TP-3-A) contains nearly fifteen percent sphene. A similar but less consistent downcoast trend also can be identified for zircon (Figure 145). The occurrence of relatively high percentages of sphene and zircon in combination with the paucity of metamorphic clasts indicates that the cliff strata in the Torrey Pines area were ultimately derived from acid plutonic rocks, most likely the Peninsular Ranges.

8.33 The sand units in the coastal cliffs at San Onofre contain less than 25 percent biotite, whereas the sand units at both Camp Pendleton and Torrey Pines contain relatively large amounts of biotite (Figure 132). Although samples in the Camp Pendleton and Torrey Pines areas contain as much as seventy percent biotite, no consistent downcoast trend seems to occur. The variation is the volume of biotite present in these areas most likely reflects differences in the depositional style and mechanical energy associated with the deposition of these strata.

8.34 Inasmuch as the strata exposed at San Onofre and Camp Pendleton were deriveds from reworking of the San Onofre Breccia which contains metamorphic minerals from the Catalina Blueschist Terrane and those exposed at Torrey Pines were derived from the acid-plutonic Peninsular Ranges, a major petrofacies (mineralogic) boundary must occur between Camp Pendleton and Torrey Pines. This relationship in conjunction with the demonstrated importance of sea cliff and bluff erosion as a local sediment source (Chapter 7) provide the potential for identifying a major petrofacies boundary along the adjacent littoral zone. The position of this boundary should provide insight concerning the amount and direction of net longshore transport in this region.

9. SUMMARY

9.1 Kuhn and Shepard (1979, 1980, 1984), Kuhn and others (1987), and this report document the episodic and site-specific nature of coastal storms as well as the associated erosion and sediment yield from 1887 to 1987 in the area from Dana Point to the United States-Mexico Border. Such information should be used to develop probabilistic elements in numeric models and the computation of sediment budgets for this coastal zone.

9.2 Although marine processes may be locally important, subaerial processes including rainfall-induced landslides, lateral and headward erosion of canyons, dissection of terrace surfaces, and gullying of cliff faces by rain wash have dominated sea cliff and bluff erosion from 1887 to present. Minimum volumes of 14.285, 9.333 and 4.368 million cubic yards of coarse-grained sediment was delivered to the coastline through the erosion of sea cliffs and bluffs at San Onofre, Camp Pendleton and Torrey Pines, respectively. These values sum to 27.986 million cubic yards. Computed rates of terrace erosion from 1889 to 1968 are very high compared to uplift rates, therefore the terraces may be short-lived features from a geologic time perspective (hundreds of thousands of years). Even higher rates of terrace erosion may have occurred during the more stormy periods of the 19th century.

9.3 The results of the mineralogic analysis of the cliff samples suggest that a major petrofacies boundary occurs between the strata exposed at San Onofre and those at Camp Pendleton. This relationship in conjunction with the demonstrated importance of sea cliff and bluff erosion as a local sediment source provide the potential for identifying a major petrofacies boundary along the adjacent littoral zone. The position of this boundary should provide insight concerning the amount and direction of net longshore transport in this region. The localized occurrence of several other minerals may provide similar information when synthesized with mineralogic data from the littoral zone.

9.4 It is clear that most of the southern California coastal observations from 1947 to 1977 were taken during an extremely benign climatic period. Although design memoranda have addressed severe wave events occurring as early as 1904 and as late as 1988, it is important that coastal planning criteria be updated to consider the effects of the great storms such as those discussed in this report.

10. GLOSSARY

Chubasco-	Spanish name for violent storms. These storms may reach hurricane intensity and occur during late summer and early fall along the northwest coast of Mexico.
Cyclonic Storm-	Windstorm moving into a low-pressure area with winds going in a counter-clockwise direction in the northern hemisphere and clockwise in the southern hemisphere.
Extratropical Cyclone-	Any cyclone scale storm that is not a tropical cyclone.
Freshet-	A flood resulting from either rain or melting snow. Usually applied only to small streams and/or to floods of minor severity.
Hogback-	Any ridge or sharp summit and steep slope of somewhat equal inclination on both flanks; resembling in outline the back of a hog.
B.P.-	Before present; by convention before A.D. 1950.
Southern Oscillation Index-	A fluctuation in the intensity of the intertropical general atmospheric and hydrospheric circulation over the Indo-Pacific region. The fluctuation is dominated by an exchange of air between the South Pacific subtropical high and sites representing the Indonesian equatorial low. The differences in sea level atmospheric pressure between sites representing the South Pacific subtropical high and sites representing the Indonesian equatorial low are used as indices to represent the Southern Oscillation.

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APPENDIX I. STORM YEAR: 1889-1900 - CONTINENTAL UNITED STATES

The U.S. Army Signal Corps records (Monthly Weather Review, December 1890, p. 324-325) give an account of the major monthly meteorological events for the period of 1889-1890.

> "The following are among the more notable meteorologic features of the year: Over a greater part of the country east of the Mississippi River the winter of 1889-'90 was the warmest on record. On January 12th destructive local storms occurred in the middle Mississippi and Ohio valleys . . ."
>
> "On this date [Jan. 12] a heavy snow storm with high wind and falling temperature, prevailed over Minnesota, the Dakotas, Nebraska, Kansas, and Iowa, and caused a general blockade of the railroads from Minnesota and the Dakotas southwestward over Kansas. On the 12th and 13th the storm along the lower lakes and on Lake Huron was one of the severest in many years, and was attended by fatalities and great destruction of property. The heaviest snow blockage ever known on the Central Pacific Railroad occurred during the latter half of the month, when about 120 miles of the railroad crossing the summit of the Sierra Nevada Mountains was blockaded. In the northern counties of Nevada the excessive snowfall caused great loss of live stock. At Stations in north Montana, north Nevada, and California the month was the coldest January on record. In the early part of the month floods destroyed millions of dollars worth of property in south Missouri, east Arkansas, and north and east Texas. In the latter part of the month floods, resulting from melting snow, caused great damage in north California. A remarkable feature of the month was the enormous quantity of Arctic ice encountered near Newfoundland and the Grand Bank where, as a rule, but little ice is encountered in January.
>
> February was the warmest February on record in the Atlantic coast and Gulf states, and in areas in the Ohio Valley and Tennessee. A cold wave the latter part of the month caused great loss of stock on the ranges in east Oregon and northeast Nevada. The great depth of snow in the cuts along the line of the Central Pacific Railroad crossing the summit of the Sierra Nevada Mountains caused serious interruption to the train service. Lakes Erie and Huron were reported practically open to navigation. Destructive floods occurred in west Oregon and north California in the early poart of the month. The rivers were generally above the danger-line in the Ohio, Cumberland, Tennessee, and lower Mississippi valleys during the later part of the month, and great damage was caused by the overflow of streams in Ohio and west Kentucky. The Verde and Gila Rivers, Ariz., overflowed their banks, and a large storage dam on the Hassayampa River, Ariz., gave way, causing loss of life and destruction of property.
>
> In March a great flood prevailed in the lower Mississippi valley, and at most of the important points along the lower Mississippi River the

water was the highest ever known. Flood conditions also prevailed along the Ohio River and its tributaries, and at the close of the month the rivers were above the danger-line from Cincinnati, Ohio, to the Gulf of Mexico. On the 27th a group of destructive tornadoes occurred in Kentucky, south Indiana, south Illinois, and southeast Missouri. In Kentucky upwards of 100 lives were lost, and property to the value of about $4,000,000 was destroyed. In Louisville alone the loss of life was 76, and many persons were injured, and the loss to property aggregated about $2,500,000. At Jeffersonville, Ind., many buildings were demolished by the Louisville tornado which crossed the river at that point, without, however, an attendant loss of life. In Illinois 7 lives were known to have been lost, and the damage amounted to at least $200,000. In southeast Missouri 4 lives were lost, where the damage to property was not heavy. Cold waves of unprecedented seasonal severity swept over the southern and southeastern states during the first and middle parts of the month and on the 2nd the heaviest snow storm in the history of the station occurred at Charleston, S. C.

In April the great flood in the lower Mississippi valley continued. Among the more important crevasses which occurred were those at Catfish Point, Miss., at the Opossum Ford levee, and at the great Morganza levee. At the close of the month not less than 15 parishes, or about one-fourth of the state of Louisiana, had been affected by the flood; about 10,000 acres had been inundated in Mississippi by the Austin crevasse which occurred March 30th; and on the Arkansas side of the river about 10,000 acres had been inundated. Water from the Nita crevasse, which occurred March 13th, had found its way into Lake Pontchartrain by means of the Manchac Passes.

In May the flood along the lower Mississippi river subsided gradually. A rise in the Red River caused the overflow of a considerable extent of country in northwest Louisiana and southwest Arkansas. Damaging floods occurred in Ontario, Canada; along the Brazos River, Tex.; in central New York and northeast Pennsylvania; along the Willamette River, Oregon; along the upper Potomac River; in Fresno and Tulare counties, Cal.; and along the Carson River, Nev. A noteworthy tornado occurred at Akron, Ohio, on the 10th. A remarkable aerolite passed over the northwest counties of Iowa on the 2nd.

In June the lower Mississippi river fell below the danger-line at New Orleans, La., on the 12th, an continued to fall slowly during the month. Floods were reported along the Carson River, Nevada, in Ontario, Canada, in central New York, northern Illinois, and southern Wisconsin. Drought injured crops and vegetation in areas in the south Atlantic and Gulf states, and in the lower Missouri valley. Destructive tornadoes occurred at Bradshaw, Nebr., and in Lee, Livingston, and Pratt counties, Illinois.

In July tornadoes, destructive to life and property, occurred in Ramsey and Wabasha counties, Minnesota, at Marshall, Minn., at Wesley, Ill., and Lawrence, Mass. Damaging drought prevailed generally in Kansas, Nebraska, and Iowa, and in areas in the Ohio

Valley and Tennessee, the Lake region, and the Atlantic coast states from Massachusetts to Alabama. Navigation was suspended on the upper Ohio River, and on the Cumberland River, at Nashville, Tenn., on account of low water, and the Arkansas River, at Fort Smith, Ark., was lower than at any time since April, 1887.

In August a West India cyclone moved from east of the Windward Islands to northwest of Bermuda from the 27th to 31st, with winds of hurricane force and loss of life and shipping. On the 19th a tornado occurred at Wilkes Barre, Pa., killing sixteen persons and destroying property the value of $600,000. On the 12th the Arkansas River was lower at Fort Smith, Ark., than at any time since 1856. Considerable damage was caused by flood along the Gila River, Arizona.

In September a notable feature was the severe cold wave which advanced from the northwest over the central valleys west of the Mississippi River on the 13th, attended by unprecedentedly low temperature for the season and early frost. Destructive floods prevailed in central and western New York, central and western Pennsylvania, West Virginia, Ohio, and Connecticut from the 10th to 15th.

In October a tornado occurred in Richmond and Robeson counties, North Carolina, on the 16th. Considerable damage was caused by freshets in the Monongahela and Little Kanawha rivers, W. Va.; a freshet occurred in the Wyoming Valley, Pa., and the Cape Fear River flooded its banks near Wilington, N.C. Very dry weather prevailed in parts of Nebraska, Kansas, Missouri, South Dakota, and south Minnesota. Destructive prairie fires occurred along the Cannon Ball, Heart, and Knife Rivers, N. Dak., in the early part of the month.

November was the driest and warmest November on record in the middle, south Atlantic, and east Gulf states, and generally along the Pacific coast. A tornado occurred near Erie, Pa., on the 17th. On the 29th a destructive storm prevailed over Newfoundland, and on the 30th a heavy gale caused damage at Bermuda Island. High water and floods were reported along the Gila and Colorado Rivers in west Arizona.

A notable feature of December was the unusually low temperature which prevailed over the extreme northeast part of the country and the anormally warm weather in the north-central districts. Precipitation was deficient over a great part of the country, the regions of greatest excess being the north Pacific coast and Cape Breton Island. A tornado passed over Jersey, Walton Co., Ga., on the 8th. Navigation closed generally on the Great Lakes, and the rivers of the north-central and northeast sections were generally closed by ice."

SUMMARY

"Among notable features of the past winter were the unusually small number of cold waves of marked severity which reached the Atlantic coast of the United States from the interior of the continent; the marked tendency of north Atlantic storms to pass southeastward over the Bay of Biscay, southeast Europe, and the Mediterranean Sea in December, to which course they were probably deflected by the area of high pressure over central Europe; and the northerly course of north Atlantic storms over the eastern part of the ocean in January, in which month the area of high pressure occupied a more southerly and westerly position than in December, and the storms were apparently deflected to a northerly course before reaching European waters."

APPENDIX II.

LARGE SCALE OCEAN-ATMOSPHERE INTERACTION

NORPAX

U.S. Navy Contract N00014-75-C-0262

J. Bjerknes, Principal Investigator

Final Report
NR 083-287
Volume II

SOME ASPECTS OF THE INFLUENCE OF ABNORMAL EASTERN EQUATORIAL PACIFIC OCEAN SURFACE TEMPERATURES UPON WEATHER PATTERNS IN THE SOUTHWESTERN UNITED STATES

by Charles B. Pyke

December 1975

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The theories of the late Dr. J. Bjerknes concerning the influence of an abnormally warm equatorial Pacific Ocean upon weather patterns in the southwestern United States are investigated further. Atmospheric circulation and precipitation patterns during the equatorial warm-water seasons of 1957-1958 and 1972-1973 are compared to those of earlier seasons of this type. These examples further confirm Bjerknes' theory that a warm

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equatorial Pacific Ocean is associated with a strong subtropical jet stream and repeated moderate to heavy storminess over the southwestern United States during winter and spring.

In Northern Hemisphere winters of cooler than normal or rapidly cooling equatorial Pacific water, large-amplitude ridges will at times form over the northeastern Pacific, bringing cold storminess and heavy snowfall, or warm and very heavy rainfall, to parts of the southwestern United States. Some historical examples of these types of patterns are discussed.

Summer and early fall precipitation over the southwestern United States, especially tropical cyclone rainfall and intense local storms, are also related--indirectly--to warm anomalies in the equatorial Pacific Ocean.

Some hydrologic applications of the relationships between precipitation and equatorial ocean temperatures are discussed, and the possibilities of seasonal forecasting are also briefly mentioned.

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Some Aspects of the Influence of Abnormal Eastern Equatorial Pacific Ocean Surface Temperatures upon Weather Patterns in the Southwestern United States

A NORPAX Contribution

by

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December 1975

INTRODUCTION

Equatorial Pacific Ocean Temperatures

Most of the time the eastern equatorial Pacific Ocean is characterized by a relatively cool tongue of water extending westward for several thousand kilometers from the west coast of South America. This phenomenon, which has been well documented and discussed by numerous meteorologists and oceanographers, results primarily from upwelling associated with Ekman divergence of the westward-flowing surface water, which is in turn driven by equatorial easterly surface winds associated with the trade wind systems of the Northern Hemisphere and especially the Southern Hemisphere.

This equatorial cooling normally reaches its seasonal maximum and minimum intensities respectively around August-October and February-April of each year--during or just after the respective seasonal maximum and minimum of the Southern Hemisphere trades. On occasion, however, the Pacific Ocean trade wind system of the Southern Hemisphere, and at times that of the Northern Hemisphere, will slow down considerably and retreat somewhat poleward over time spans of many months or even several years, thus greatly weakening the easterly surface winds along the equator and allowing an abnormal warming of the eastern equatorial Pacific waters to take place (largely through horizontal advection)--sometimes to the point where the cool tongue has disappeared entirely. In the more extreme cases of this eastern equatorial warming, very warm water will flow southward along the west coast of Peru to well south of the equator, giving rise to the condition known as "El Niño" (see Bjerknes, 1961, 1966a, 1966b, 1974b; Miller and Laurs, 1975; Quinn and Burt, 1970; and numerous other articles written on the subject).

It has been aptly demonstrated by the late Dr. J. Bjerknes (1966a, 1966b, 1969a, 1969b, 1969c, 1972, 1974a, 1974b, and other articles) that during periods in which this low-level easterly wind flow along the Pacific equator (with a corresponding return westerly flow aloft--completing a zonal circulation termed by Bjerknes as the "Walker Circulation") greatly diminishes or ceases, and the equatorial waters warm up, atmospheric convection in the equatorial zone increases, and this in turn serves to increase the meridional Hadley Circulation in each hemisphere, particularly the winter hemisphere. Through angular momentum considerations, this strengthening of the Hadley Circulation results in an acceleration of the subtropical jet stream across and east of the longitude belt of the anomalously warm equatorial waters--a phenomenon which in turn not only affects quite profoundly the local weather conditions in the general vicinity of this jet stream, but which very frequently effects large-scale, long-term tropospheric anomalies in quite distant parts of the globe (through atmospheric teleconnections). The influences of anomalously warm equatorial Pacific waters usually reach their maximum during periods in which such an anomaly is coincident with the normal seasonal maximum of equatorial ocean temperatures--a time of the year which also happens to be the normal seasonal maximum of the subtropical jet stream in the Northern Hemisphere: late winter.

Influences of Warm Equatorial Water upon Southern California Precipitation

Among other specific meteorological effects of anomalously high equatorial Pacific Ocean temperatures, Bjerknes has noted the connection between abnormally warm equatorial Pacific waters and heavier than normal precipitation in southern California: The increased intensities of the subtropical jet stream over or just south of southern California during the winter which result from an equatorially enhanced Hadley Circulation tend to dynamically favor an increase in tropospheric cyclonic activity and precipitation in the vicinity of southern California (see especially Bjerknes, 1969b).

Bjerknes (1961) discusses the major 1939-1941 "El Niño" condition, and on a number of occasions he discussed the role of the associated warm equatorial Pacific Ocean waters in helping to produce the great abundance of precipitation during the rainy season of 1940-1941 in southern California and other nearby regions--a season in which a great many precipitation stations recorded between July 1940 and June 1941 well in excess of twice their normal annual totals.

Bjerknes (1966a, 1966b, and in later papers) has also discussed the response of the equatorial and Northern Hemisphere tropospheric circulations to the abnormal warmth of the equatorial Pacific Ocean during the season of 1957-1958 (another period of "El Niño"); and he has investigated in even more detail the effects upon the atmospheric circulation and associated weather patterns of the alternately warmer and cooler equatorial ocean years between 1962 and 1966 (Bjerknes, 1969a, 1969b, 1972, 1974a, and other papers).

In early 1972 still another "El Niño" condition developed along the west coast of South America, and the equatorial waters for several thousand kilometers west of that continent rapidly warmed up to anomalously high levels (see Miller and Laurs, 1975), as they had done during 1939-1941 and again in 1957-1958. This time, even though southern California was in the midst of the worst winter-spring drought in its history (only 0.13 inches of rain in Los Angeles from January through March 1972--see article by Namias, 1972), Dr. Bjerknes, upon the reports of the rapidly warming ocean conditions and incipient El Niño off the west coast of South America, predicted that the following winter (1972-1973) would likely be a wet one for southern California. He cited the developing equatorial ocean warm anomaly and implied the (by then) well-known teleconnection theories which he had developed.

Prof. Bjerknes' predictions came true, as the strong subtropical jet stream developed over the eastern Pacific Ocean and southwestern North America during the winter of 1972-1973, bringing well above normal seasonal precipitation to southern California and many other parts of the southwestern United States, with severe weather and heavy precipitation also extending into the central and eastern parts of the nation during the spring.

In this paper an attempt is made to describe and directly compare some of the atmospheric circulation and precipitation patterns of 1972-1973 with those of 1957-1958--a very similar year meteorologically--and then to relate these patterns, their similarities, and their differences to the similarities and differences between the equatorial Pacific Ocean temperature anomalies of the two seasons. Brief comparisons are also made to other years of abnormally warm equatorial Pacific water, as well as to certain years of cooler than normal equatorial Pacific water, and some of the hydrologic effects of the anomalous meteorological conditions associated with warmer and cooler equatorial Pacific conditions are discussed.

THE 1972-1973 RAINY SEASON COMPARED TO 1957-1958 AND OTHER WET YEARS

In many ways the atmospheric patterns and associated weather patterns during the greater winter rainy season of 1972-1973 over the southwestern United States were very similar to those experienced in 1957-1958 and in certain other years of anomalously high equatorial Pacific Ocean temperatures, such as the season of 1940-1941. There were, however, some significant differences, as one should expect. In Figs. 1a-18a the author has reproduced from the series of articles in Monthly Weather Review, entitled, "The Weather and Circulation of ... (month and year) ...," the mean 700 millibar height chart for non-summer months during the periods of 1957-1958 and 1972-1973 in which the Northern Hemisphere mid-latitude circulation appears likely to have been significantly affected by the anomalous warming of the equatorial Pacific Ocean. In Figs. 1b-18b the author has reproduced for each corresponding month the percentage of normal precipitation map for the United States (the 1957-1958 maps from Monthly Weather Review articles, and the 1972-1973 maps from U. S. NOAA and U. S. Dept. of Agriculture, 1972-1973). For more complete accounts and descriptions of the monthly weather patterns of the two seasons, the reader is referred to the above-mentioned series of articles in Monthly Weather Review, plus the monthly summaries in Weatherwise.

In both sets of monthly maps (Figs. 1a-18a) one can see in general a tendency for a strong west-to-east flow of air at 700 millibars (a reflection of an even much stronger jet stream higher in the troposphere) across the northeast Pacific and/or North America at moderately low latitudes. (Note that the 1972-1973 maps have been analyzed for every 30 meters, while the 1957-1958 maps were analyzed for only every 200 feet, or 61 meters. Thus for a given 700 mb height gradient, approximately twice as many lines would appear in the 1972-1973 maps as in the 1957-1958 maps.) The 1957-1958 maps show the departures of the heights from normal, and one can see significant and sometimes very large negative departure fields north of most of these subtropical wind maxima, especially during the midwinter months of January and February 1958.

The 1957-1958 Season

The anomalous circulation conditions of 1957-1958 appear to have perhaps begun early in 1957--possibly as early as February or March, as the circumpolar vortex expanded farther equatorward than normal, and as westerly winds aloft increased over portions of the subtropical northeastern Pacific Ocean and southern United States (MWR, Feb-Apr 1957).[1]

By May 1957 the anomalous pattern was very evident (see Fig. 1a), as 700 mb heights were below normal over most of the region from 20°N to 45°N latitude and from 170°W to 90°W longitude, and as the westerly winds aloft (especially at the higher levels, e. g., 200 mb) were considerably stronger than normal in portions of this belt (MWR). In particular, there was a strong 200 mb mean jet stream in May 1957 across central Baja California and east-northeastward through the south central United States, roughly along (i. e., above) the 10,200-foot 700 mb height contour line of Fig. 1a. Precipitation during May 1957 was greatly above normal over nearly all of the southwestern and south central parts of the country (Fig. 1b), and extensive flooding occurred in many areas (MWR). A record number of tornadoes (231) for the month of May in the United States (up to that time) was also reported in 1957 (MWR).

After the summer months of 1957 (a season in which the Hadley Circulation and the subtropical jet stream either disappear or else run at an absolute minimum of intensity), the anomalous circulation patterns of 1957-1958 began to reappear during the early

[1] an abbreviated form of reference used in this paper to designate the many articles appearing in Monthly Weather Review entitled, "The Weather and Circulation of..." The appropriate months and years are also included whenever there may be a question as to which article or articles are referenced. Note that after 1960 all such articles describing conditions for a given month appear in the Monthly Weather Review issue of three months later.

fall (Figs. 2-3). In September 1957 (Fig. 2a) the 700 mb heights were below normal between 30°N and 40°N latitude from near the west coast of California to beyond the International Date Line, while in October (Fig. 3a) the negative anomaly--although very slight in some longitudes--extended across this latitude belt from west of the Date Line eastward all the way into the western Atlantic Ocean. The occurrence of much heavier than normal precipitation over a large portion of the southwestern United States during October 1957 (Fig. 3b) undoubtedly received a substantial contribution from the presence of a persistent short wave trough at 700 mb over the west coast of the United States (Fig. 3a), which appears to have had its beginnings during the month of September (Fig. 2a). Warmer than normal ocean temperatures west of California and Baja California during this period (Eber, Saur, and Sette, 1968; Namias, 1959; and others) are also very likely to have contributed significantly to the heavy early fall precipitation in the southwestern United States during 1957. (See also the discussion of summer and early fall conditions in a later section of this paper.)

From November through January of 1957-1958 (Figs. 4a-6a) a ridge generally prevailed over or off the west coast of North America, but the strong subtropical jet stream which is likely associated with the equatorially intensified Pacific Hadley Circulation appears to have developed fully during January over the longitudes 170°E-140°W (Fig. 6a). By February 1958 this jet stream and the associated negative 700 mb height anomaly had moved about 10 degrees of longitude farther to the east (Fig. 7a), and the jet also appears to have broken under the blocking high that was located over the Pacific Northwest United States and western Canada (compare the 10,200-foot height contour line of Fig. 7a (February) with that of Fig. 6a (January)). This brought a series of vigorous extratropical Pacific cyclones, roughly following the the path of the subtropical jet stream, onto the coast at relatively low latitudes, and the effects of this resulted in considerably heavier than normal precipitation over much of the southwestern United States (Fig. 7b).

During March and April of 1958 much of the southwest United States continued very wet (Figs. 8b-9b), as a depressed quasi-zonal flow and strong subtropical jet stream (especially at the higher levels) continued across the lower latitudes of the eastern Pacific and North America (Figs. 8a-9a), with a tendency for somewhat more ridging in the eastern Pacific and a somewhat more northwest-to-southeast storm trajectory--a change in pattern which seems to be typical for this time of the year (see discussion by the author in another paper: Pyke, 1972--Sec. III.A.2.).

By May 1958 (Fig. 10a) the pattern had changed very considerably, and any influence of a warm equatorial Pacific-generated Hadley Cell upon the Northern Hemispheric circulation had completely disappeared. Small areas of heavier than normal precipitation in the far southwestern States during May 1958 (Fig. 10b) were likely the result of a small mean trough off the west coast (Fig. 10a) and the augmentation of moisture and instability by continued warmer than normal subtropical ocean surface temperatures off the coast.

The severe weather activity (tornadoes, severe thunderstorms, floods, etc.) over the central United States was also considerably less extensive during the spring of 1958 than during the previous year (MWR, Apr-May 1958).

The 1972-1973 Season

The anomaly patterns characteristic of the greater winter season of 1972-1973 did not appear prominently prior to the summer of 1972, as seems to have been the case in 1957. By contrast, the mean monthly maps for March and April of 1972 (not shown) displayed generally middle- to high-latitude westerly to northwesterly flow across the eastern Pacific and parts of North America (MWR, Jun-Jul 1972).[1] The primary reason for this difference between the patterns of early 1957 and early 1972 would seem likely to be that the warming of the equatorial Pacific Ocean appears to have taken place a few months earlier in 1957 than did the corresponding warming in 1972 (see later discussions). Only during May of 1972, as the equatorial Pacific Ocean began to warm up significantly, was there a hint of any mean low-latitude subtropical jet stream formation. This occurred along the extreme southern United States, i. e., the Gulf Coast region (MWR), and may have been the first manifestation of a weak Hadley Cell intensification over the extreme eastern Pacific (east of 120°W)--the longitudes in which equatorial and north tropical Pacific Ocean temperatures were now running a few degrees above normal (U. S. National Marine Fisheries Service, 1960 et seq.).

[1] articles in the June and July 1972 issues of Monthly Weather Review, describing the weather conditions for the months of March and April 1972 respectively.

It is also very interesting to note that the anomalous equatorial warming, which had finally become well established in the area off the immediate west coast of South America by June 1972 (Miller and Laurs, 1975; U. S. National Marine Fisheries Service, 1960 et seq.) may have been indirectly responsible for helping to create one of the greatest United States flood disasters of recent years: that of the northeastern States associated with Tropical Storm Agnes (see the interesting article by Namias, 1973a; see also MWR for September 1972--article on conditions of June 1972).

From October of 1972 through April of 1973 the atmospheric and precipitation patterns exhibited numerous striking similarities to those of 1957-1958 (compare especially the precipitation patterns, month by month: Figs. 11b-17b vs. Figs. 3b-9b). Although both seasons appear to have been characterized by the development and persistence of an unusually strong subtropical jet stream across the eastern north Pacific and the southern United States, 1972-1973 (Figs. 11a-18a) seems to have been dominated by a more systematic eastward progression of a major long wave tropospheric trough (see Namias, 1974; plus MWR).

In October 1972 (Fig. 11a) an even more intense mean short wave trough developed along the west coast of California than occurred in October 1957 (Fig. 3a), with even greater precipitation over portions of central California and Arizona (Fig. 11b vs. Fig. 3b). Again, as in 1957-1958, this heavy precipitation is likely to have been augmented by the fact that ocean temperatures off California and Baja California during this period were several degrees above normal (U. S. National Marine Fisheries Service, 1960 et seq.)--perhaps by no coincidence (see later sections of this paper).

This mean west coast trough of October 1972 progressed less rapidly eastward over the next three months (Figs. 11a-14a) than did the one of October 1957 (Figs. 3a-6a). Therefore there was generally somewhat heavier precipitation over most of the southwestern States from November 1972 through January 1973 (Figs. 12b-14b) than during the corresponding months of 1957-1958 (Figs. 4b-6b). At the same time the influence of the eastward-progressing upstream Pacific Ocean trough began to be felt on the west coast a little earlier in 1973 (Figs. 14a-b) than in 1958 (Figs. 6a-b). Figs. 14a-15a (compared to Figs. 6a-7a) also show that the mean flow aloft--and hence the average trajectories of the storms reaching the southwestern United States--tended to be more nearly westerly across the eastern Pacific (and hence somewhat less tropical in character) during January and February of 1973 than was the case during the same months of 1958, when the mean flow was from the south of west. This is reflected by the fact that 700 mb heights over the mid-latitude central and eastern north Pacific ran generally 50-150 meters higher during January 1973 and 50-100 meters higher during February 1973 than they did in 1958, while those near the California coast were generally 20-40 meters lower in 1973.

By March and April 1973 (Figs. 16a-17a) the major trough was somewhat larger and centered farther to the south and east than in 1958 (Figs. 8a-9a), as a considerably more prominent ridge built in the eastern Pacific. The amplification of this ridge, although perhaps a typical phenomenon for this season (as discussed earlier), was in 1973 far greater in magnitude than normal. It would seem possible that the building of this ridge may have been in part a reflection of the development of a "Hadley Anticyclone" (as termed by Bjerknes, 1969b, and other articles)--a warm, high-level anticyclone presumably generated by the flux of sensible and latent heat from the warmer and more active than normal eastern equatorial Pacific convergence zone. It also seems likely, though, that the persistence (in location and amplitude) of this anomalously strong mean ridge was to a great extent a response to developments arising from anomaly patterns in the ocean surface temperatures of the mid-latitude north Pacific (Namias, 1974).

The greater depth of the trough over the southwestern United States during March and April of 1973 probably accounts for the somewhat greater precipitation over this region during those months, especially during March, compared to the corresponding period in 1958 (Figs. 16b-17b vs. Figs. 8b-9b). The deeper trough over this area during the spring of 1973, coupled with the fact that the storm trajectories had also been more nearly westerly (and hence the storms somewhat cooler) during January and February 1973 (as opposed to south of west and somewhat warmer in January-February 1958), may have been to a large extent responsible for the fact that the spring snow packs in the southwestern Rocky Mountains, particularly in Arizona, had considerably more water content in 1973, especially at elevations of 6000-8000 feet above sea level, than they had had in 1958 (U. S. Soil Conservation Service, 1958, 1973).

Farther east there was considerably heavier precipitation over most portions of the central United States during the winter and spring of 1973 (Figs. 14b-18b) than during the early part of 1958 (Figs. 6b-10b). Heavy winter and early spring snows (which later melted), plus heavy and persistent spring rainfall over vast areas of the nation's midsection, led to some of the worst flooding in history in the Mississippi Valley during 1973 (see MWR, Jun-Jul 1973; Namias, 1974; plus numerous articles and data summaries by the National Weather Service and others). The year 1973 also saw a record number of tornadoes across the nation. During the first five months of 1973, according to reports (National Weather Service teletype and other sources) released by Allen Pearson, Director, National Severe Storms Forecast Center, more than 700 tornadoes had been reported, compared to the previous record of 504 for the corresponding period of 1957 (see earlier discussion on the 1957 tornadoes).

From these accounts of events during 1957, 1958, 1972, and 1973, one can readily see that the springtime severe weather episode in the central United States associated with the 1957-1958 anomalous atmospheric circulation period occurred during the early portions of the anomaly, while the severe weather episode associated with the 1972-1973 anomaly occurred near the end. There appear to be at least two reasons for this difference: First, there are the differences in the equatorial and northeastern tropical Pacific Ocean temperature anomalies--the 1957-1958 warming appears to have both begun and reached its peak slightly earlier with respect to the corresponding calendar years than did the equatorial warming of 1972-1973 (Eber et al., 1968; Allison et al., 1972; Miller and Laurs, 1975; U. S. National Marine Fisheries Service, 1960 et seq.). Secondly, and perhaps more importantly, there were significant differences in the mid-latitude tropospheric wave patterns between the two periods, including the greater amplitude of, and stronger circulation associated with, the progressive long wave trough in 1973 (Figs. 15a-18a), compared to the conditions in 1958 (Figs. 7a-10a). These differences in patterns are likely to have been determined to a considerable extent by forcing from the north Pacific (and perhaps even Atlantic) Ocean temperature anomalies and from anomalies in land surface conditions, such as snow cover (see Namias, 1959, 1974, and numerous other articles).

During these two anomalous greater winter seasons the precipitation in the southwestern United States was caused primarily by a prolonged and repeated march of cyclones from west to east across the subtropical eastern Pacific Ocean and into southern California, with the storm tracks turning somewhat more toward a northwesterly-to-southeasterly direction during the spring, especially in 1973. These storms, as could be seen for the 1972-1973 season on satellite photographs (U. S. NOAA, 1973 et seq.; plus National

Weather Service facsimile charts), would frequently be enhanced by strong bands of cloudiness streaming northeastward from somewhat wider and more intense than normal equatorial Pacific cloud bands associated with the intertropical convergence zone(s)--a further confirmation of Dr. Bjerknes' theory on the effects of abnormally warm equatorial Pacific Ocean temperatures upon mid-latitude circulation patterns.

No individual storm during either of these seasons produced any truly excessive amounts of precipitation other than in very localized areas (mostly from embedded thunderstorms), but the sum total of all of the storms in each season (1957-1958 and 1972-1973) raised the seasonal rainfall totals (as measured from July through June, or in some cases, from October through September) to levels of 1.5 to 2 times the normal values at many stations during each precipitation year (U. S. Weather Bureau, 1964-1965; U. S. Weather Bureau, ESSA, and NOAA, 1897 et seq.).

The 1940-1941 Season

Not as much information is readily available concerning the oceanic and atmospheric anomaly in 1940-1941, compared to those of 1957-1958 and 1972-1973. Precipitation data do show that very wet conditions prevailed over the southwestern United States throughout the entire season of 1940-1941, with well over twice the normal annual precipitation amounts at many stations, and approaching three times the normal annual totals at some (U. S. Weather Bureau, 1953 ff; U. S. Weather Bureau, ESSA, and NOAA, 1897 et seq.).

Surface weather maps from the Daily Synoptic Series (U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.) show from December 1940 through April 1941 (the period of greatest positive precipitation anomaly) a nearly unending series of low-latitude storms traveling across the eastern Pacific Ocean, often splitting off from the main cyclonic circulation (located over the ocean), and entering southern California or even northern Baja California, with each storm dropping substantial precipitation over the far southwestern United States. The crude upper air charts (3000 dynamic meters--near 700 mb) for December 1940 (the last month before World War II for which upper air charts are published--U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.) show (to the extent of the sparse data coverage of those days, especially over the ocean) the tendency for an expanded polar vortex and strong subtropical jet across the eastern Pacific Ocean and the tendency for a splitting of the flow as it approaches the west coast of the United States, with a weak blocking high located over the Pacific Northwest and western Canada--a pattern quite similar to the mean patterns of February 1958 (Fig. 7a) and February 1973 (Fig. 15a). This tendency for blocking and splitting of the flow certainly seems to reflect the presence of a strong and persistent subtropical jet stream across Baja California--likely enhanced by the Hadley Circulation emanating from the warm equatorial waters to the south, and perhaps also the presence of a broad "Hadley Anticyclone" located over the subtropical latitudes of the central and east central Pacific--an anticyclone generated by the warm air aloft in these longitudes associated with the above-mentioned Hadley Circulation (see Bjerknes, 1969b, and other articles).

EQUATORIAL PACIFIC OCEAN SURFACE TEMPERATURES

As for some of the details of the equatorial Pacific Ocean surface temperature patterns during the anomalous seasons of 1940-1941, 1957-1958, and 1972-1973, little can be said about 1940-1941 other than that the anomaly was large, long-lasting, and apparently very widespread (see Bjerknes, 1961). As for the other seasons, different sets of monthly or seasonally averaged maps are available for the two periods, using different units of temperature.

For the 1957-1958 period, monthly mean isothermal analyses are available in degrees Celsius from Eber, Saur, and Sette (1968), and 3-monthly averages of the departures of these Eber et al. data from long-term means (Laviolette and Seim, 1969) have been prepared (also in $^{\circ}$C) by Allison et al. (1972). A sample of three of these seasonal departure maps of Allison et al., covering the period of the greatest positive equatorial ocean temperature departures of the 1957-1958 anomaly, have been reproduced as Fig. 20 of this paper.

For the 1972-1973 period, monthly mean isothermal analyses and departures from long-term means (a somewhat different set of long-term means from those used by Allison et al., 1972--see U. S. National Marine Fisheries Service, 1960 et seq.; Miller and Laurs, 1975) are mapped, both in degrees Fahrenheit. Two departure maps of this National Marine Fisheries Service series, representing approximately the peak of the 1972-1973 equatorial warm anomaly, have been reproduced in this paper as Figs. 21 and 22. It should also be noted that the shading patterns in Figs. 21 and 22 (negative temperature anomalies) are opposite to those of Fig. 20 (positive anomalies). With all of the above in mind, it can easily be seen that a careful comparison of equatorial ocean temperature patterns between the two seasons 1957-1958 and 1972-1973 is difficult at best!

Perhaps the primary differences between the two periods of anomalously warm equatorial ocean temperatures which can be detected from an examination of the two different sets of maps is that the 1957 warming appears to have begun perhaps a little earlier in that year than the latter warming did during 1972. The peak in 1957 may have also occurred a bit earlier, and there is no doubt that the rebound to cooler than normal conditions occurred <u>much</u> more rapidly in 1973 than it did during the late 1950's.

Sea Level Pressure Differences

Some of these differences between the two seasons 1957-1958 and 1972-1973 can be seen indirectly in Fig. 23. This figure, reproduced from Quinn (1975), exhibits the 12-month running means of the differences in sea level pressure between Easter Island (in the southeastern Pacific Ocean at 27°10'S, 109°26'W) and Darwin, Australia (12°26'S, 130°52'E). This pressure difference has been correlated by Bjerknes (e. g., 1974b), Quinn (1974, 1975; Quinn and Burt, 1972), and others to the "Southern Oscillation," i. e., the ebb and flow of the equatorial zonal "Walker Circulation," and hence to the equatorial Pacific Ocean temperatures (see also publications by Walker (e. g., Walker and Bliss, 1932) and Berlage (e. g., 1966)).

When the E-D pressure difference (as it is termed by Quinn) is high, the Walker Circulation is strong, and the eastern equatorial Pacific Ocean surface temperatures are relatively low. When the pressure difference is low, the Walker Circulation is weak, and the equatorial ocean temperatures are (or are rapidly becoming) high. Hence the major peaks in the E-D pressure difference curve of Fig. 23 correspond to periods of below normal eastern equatorial Pacific Ocean temperatures, whereas the troughs in the curve correspond to equatorial oceanic warm anomalies and, at times, El Niño conditions.

One can see in Fig. 23 that indeed the conditions leading to the 1957 equatorial warming (compared to those of 1972): (1) began earlier in the 1957 case (actually in early 1956, according to the 12-month running means of the E-D pressure difference), (2) advanced somewhat more slowly, (3) peaked earlier, and (4) recovered much more slowly than did the 1972 warm anomaly.

Other Seasons, 1938-1974

One can also see in Fig. 23 the indications of two other significant warm equatorial ocean anomaly periods, 1951-1953 and 1965, with two somewhat more minor warmings in 1963 and 1969. In conjunction with the 1965 warming there was a rather brief period of anomalous atmospheric circulation in the Northern Hemisphere during November and December of 1965--a period during which southern California and Arizona experienced very heavy rainfall from subtropical sources (see Bjerknes, 1969a, 1972, 1974a, and especially 1969b). Quite heavy rainfall also hit southern California in November 1963, presumably from a similar, although weaker, influence from the equatorial Pacific (see Bjerknes, 1969b, and other articles).

The seasons 1951-1952 and especially 1968-1969 were also very wet in central and southern California. A careful examination of the weather maps for those years, however, would seem to indicate that the heavy precipitation of these rainfall seasons probably did not result primarily from the above normal equatorial Pacific Ocean temperatures, but rather from higher latitude oceanic and atmospheric anomalies (e. g., Figs. 19a, c-f)--as will be discussed later.

The record of sea level pressure at Easter Island (and hence the E-D pressure difference) does not go back to the 1940-1941 season. However, the Darwin pressure record itself goes back to the year 1882; and since Darwin's pressures alone also happen to be a fairly good indicator of the Southern Oscillation conditions, according to Quinn and Burt (1970) (the higher the pressure at Darwin, the weaker the Walker Circulation, and the higher the equatorial ocean temperatures--see Fig. 24), one can obtain from the Darwin sea level pressure record a fairly good estimate of the temporal behavior of the average equatorial ocean temperatures in the eastern Pacific.

Fig. 25, which has been reproduced from Quinn (1974), shows the Darwin pressure record extending back to 1938. In this figure one can see by implication that the major equatorial warming of 1940-1941, which actually extended over the period 1939-1942, was considerably more extensive in time and likely greater in amplitude than was any other equatorial warm anomaly since that time (see both Figs. 24 and 25 for the complete 12-month running means of Darwin sea level pressure from 1938 to 1974).

Equatorial Pacific Island Rainfall and the Southern Oscillation

Another good indicator of the equatorial Pacific Ocean temperature anomaly is the average rainfall at the central equatorial Pacific islands: the warmer the ocean, the greater the convective rainfall (see papers by Bjerknes, Quinn, Krueger, Allison et al., and numerous other authors). In Fig. 23, Quinn has indicated by arrows the periods of anomalous equatorial Pacific rainfall; these coincide very well with the major dips in the 12-month running means of the E-D pressure difference.

Allison et al. (1972) have computed a correlation coefficient of +0.93 between 12-month running means of the equatorial Pacific Ocean temperatures, 5°N to 5°S, 80°W-180°, and the 12-month running means of the average rainfall at eleven central equatorial Pacific islands, centered in time one month later than the ocean temperatures. Fig. 26, reproduced from Allison et al. (1972), shows this excellent correlation over the period 1949-1969. Allison et al. were thus able to graphically extend back to the year 1904 a reasonable approximation of the equatorial Pacific Ocean temperature anomalies through the 12-month running means of the equatorial Pacific island rainfall, as well as the 12-month running means of the Darwin, Australia sea level pressure. These graphs have been reproduced in this paper as Figs. 27-28.

Allison et al. have also derived eastern Pacific Ocean surface temperature anomalies for other tropical latitude belts back to 1905, and their charts of these quantities have been reproduced here as Fig. 29 (observed, 1949-1970) and Fig. 30 (observed and derived, 1905-1949).

In Table 1 of this paper the author has reproduced from Quinn and Burt (1970) their Table 1, in which they have compiled: (a) years of significant rises in the mean sea level pressure at Darwin, Australia; (b) periods of, and extensiveness of, rainfall at a number of near-equatorial Pacific island stations; (c) a measure of the prediction value of the Darwin pressure rise for the equatorial island rainfall; and, for comparative purposes, (d) a listing of El Niño disturbances along the west coast of South America.

Table 1 (from Quinn and Burt, 1970):

TABLE 1. Darwin pressure rise in relation to rainfall period and its prediction, and El Niño disturbances.

Pressure rises: Period and amount[a]	Rainfall period and extensiveness[b]	Prediction value[c]	El Niño disturbance[d]
1890–91 (L)	?	?	yes (1891)
1895–96 (M)	1896–97 (?)	yes	NR[e]
1898–99 (M)	1899–00 (E)	yes	(1899?)
1900–01 (S)	1902–03 (E)	yes	NR
1900–02 (L)	1902–03 (E)	yes	NR
1903–04 (S)	1904–06 (E)	yes	NR
1903–05 (S)	1904–06 (E)	yes	NR
1910–11 (L)	1911–12 (E)	yes	(1911?)(1912?)
1912–13 (M)	1913–15 (E)	yes	NR
1912–14 (L)	1913–15 (E)	yes	NR
1917–18 (VL)	1918–20 (E)	yes	(1917?)(1918?)
1922–23 (S)	1923–24 (NE)	yes	(1923?)
1924–25 (VS)	1925–26 (NE)	yes	yes (1925)(1926?)
1928–29 (S)	1929–31 (E)	yes	(1930?)(1931?)(1932?)
1928–30 (S)	1929–31 (E)	yes	(1930?)(1931?)(1932?)
1938–39 (S)	1939–42 (E)	yes	yes (1939–41)
1938–40 (VL)	1939–42 (E)	yes	yes (1939–41)
1943–44 (S)	(NE?)	(?)	NR
1945–46 (S)	1946 (NE)	no	NR
1948–49 (VS)	1948 (NE)	no	NR
1950–51 (M)	1951 (NE)	no	(1951?)
1952–53 (S)	1953 (NE)	no	yes (1953)
1956–57 (L)	1957–58 (E)	yes	yes (1957–58)
1958–59 (S)	1958–59 (NE)	no	NR
1960–61 (S)	1961 (NE)	no	NR
1962–63 (S)	1963–64 (NE)	yes	NR
1964–65 (VL)	1965–66 (E)	yes	yes (1965–66)

[a] Amount symbols in parentheses are: VL—very large; L—large; M—moderate; S—small; VS—very small. See text for definitions.
[b] Extensiveness symbols are: E—extensive; NE—nonextensive; ?—lack of sufficient precipitation data.
[c] Question mark indicates lack of precipitation data.
[d] Question mark indicates years not generally accepted as El Niño years but some confirming evidences available.
[e] NR, no reports.

Figs. 31-33 depict still another indicator of conditions in the equatorial Pacific Ocean. In Figs. 31-32 the author has plotted the values of the Southern Oscillation Indices, as tabulated by Berlage (1966). These indices were computed by Berlage for the months of April-September (his Table 9) and for October-March (his Table 10) over the period of years 1841-1960, using sea level pressure anomalies at up to ten stations (including Darwin, Australia) straddling the equatorial belt in the region surrounding the Indian Ocean. The index values from these two tables of Berlage have been plotted separately in Fig. 31, and have been combined into a single graph in Fig. 32. The units of the ordinate in Figs. 31-32 are millibars, and the vertical lines designating the years represent the midpoints of those calendar years (the April-September indices are plotted on the lines, while the October-March indices are plotted midway between the lines).

Low values on these graphs indicate generally lower than normal sea level pressure in the region of Indonesia and the Indian Ocean, and hence a well-developed Walker Circulation (having strong east-to-west low-level winds), with consequently large-scale upwelling and below normal ocean temperatures in the eastern equatorial Pacific. High values imply weaker Walker Circulation and the likelihood of above normal equatorial Pacific Ocean temperatures.

Also entered in Figs. 31-32, for comparison, are the periods of anomalous equatorial Pacific island rainfall and the years of reported El Niño conditions. The symbols used are the same as those of Fig. 23, but with extensive and nonextensive equatorial rainfall differentiated. Data for El Niño conditions are obtained from Fig. 23 and Table 1 for the period since 1890, and from Frijlinck (1925) for the earlier years. Quinn and Burt (from whom Fig. 23 and Table 1 are obtained) list both the generally accepted El Niño years (EN) and those not generally accepted but for which some confirming evidence is available (EN?). The tabulations of Frijlinck apparently include only the more prominent El Niño years (and are entered in Figs. 31-32 as EN). Data for equatorial Pacific island rainfall are obtained from Table 1 (Quinn and Burt, 1970) and from Figs. 26-28 (from Allison et al., 1972), and are available only for the period since approximately 1895 (even the extensiveness of the 1896-1897 equatorial island rainfall period is unknown because of very sparse data).

In Figs. 31 and 32, just as in Figs. 23-27 and 29-30, one can easily see the major equatorial warming of 1957-1958 and the even greater and longer-lasting warm anomaly of 1939-1942. The major cool periods of 1949-1950 and 1954-1956 also show up in each of these figures, as do the minor warm period of 1951-1953 and the other minor features between 1938 and 1960.

Fig. 33 is a graph of the Southern Oscillation as computed by Sir Gilbert Walker for the period 1875-1930 (and reproduced here from Walker and Bliss, 1932--their Chart 19).

Dr. Walker's Southern Oscillation Indices have been computed, tabulated, and graphed separately for the (Southern Hemisphere) winter season (June-August) and for the summer (December-February), using different sets of meteorological parameters and different computational formulae for each of the two seasons (see Appendix of Walker and Bliss, 1932, for tabulations of the Southern Oscillation Indices by year). The ordinate in Fig. 33 (unlike Dr. Berlage's indices, which are measured in millibars of sea level pressure anomaly) is dimensionless, and represents a rather complicated linear combination of various parameters, including pressure, temperature, rainfall, and flood flow--each divided by its own standard deviation (see text of Walker and Bliss, 1932, for a complete description). Each vertical unit (distance between horizontal lines) in Fig. 33 represents two (dimensionless) units of Walker's Southern Oscillation Indices (as tabulated in the Walker and Bliss Appendix).

Because of the different parameters used by Walker and by Berlage (the only elements in common are the Darwin sea level pressure for the Southern Hemisphere winter season computations, and the Darwin and Capetown pressure for the summer), and because of the different computational methods and the different periods of months employed, there are naturally differences in the computed Southern Oscillation Indices of Walker and of Berlage, including opposite algebraic signs. Despite these differences, the correlation coefficients computed (by this author) between these indices of Walker and Berlage over the complete common period of tabulations are very high (albeit negative because of the algebraic sign differences): -0.86 for the Southern Hemisphere winter (April-September for Berlage, June-August for Walker), and -0.89 for the Southern Hemisphere summer (October-March for Berlage, December-February for Walker). These correlations can be seen visually by carefully comparing Figs. 31 and 33.

EQUATORIAL WARM PERIODS AND ATMOSPHERIC ANOMALIES OF EARLIER YEARS

Available Data

Although there is in general considerably less meteorological and especially oceanographic information available for the years prior to World War II than for the more recent years, particularly over the Pacific Ocean, the various indices of the Southern Oscillation, as computed by Bjerknes, Quinn, Allison et al., Berlage, Walker and Bliss, and others, based upon the available records of sea level pressure and rainfall in the tropical Pacific Ocean - Indonesia - Indian Ocean domain, are nevertheless surprisingly useful in studies of the equatorial Pacific Ocean's influence upon precipitation in the southwestern United States.

As with the more recent warm anomalies already discussed, the Southern Oscillation indices of Figs. 26-33 and Table 1 can be compared to the various atmospheric circulation patterns and to the corresponding precipitation anomalies over the southwestern United States. The atmospheric circulation anomalies can be seen for the period since January 1899 from the daily synoptic weather maps of U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA (1943 et seq.) plus unpublished monthly mean sea level pressure charts compiled from these daily maps by the U. S. Weather Bureau (now National Weather Service), Suitland, Maryland.

Daily and monthly precipitation data in the southwestern United States are routinely available at many stations back to around the beginning of the 20th Century (U. S. Weather Bureau, ESSA, and NOAA, 1897 et seq.; U. S. Weather Bureau, 1931 ff, 1953 ff, 1964-1965). Prior to that time the data become increasingly sparse, although there are monthly totals published (U. S. Weather Bureau, 1931 ff) for quite a number of now-discontinued stations and for several stations which have continued in existence from around the middle of the 19th Century through the present.

In one portion of the southwestern United States--the southern California coastal region--these few early precipitation station records have been supplemented with runoff records and lake level records by H. B. Lynch (1931) to form a set of rainfall indices for each rainfall season back to the beginnings of these records. These indices have been extended by Lynch even further back in time through the incorporation of qualitative accounts (Spanish Mission records, etc.) of rainfall, streamflow, and the degree of success or failure of crops.

Table 2 (reproduced from Lynch, 1931) depicts these rainfall indices (which are designed to represent an approximate per cent of normal annual precipitation) for four areas of coastal southern California, each over all or part of the period from 1769 to 1930. These total-year indices represent almost exclusively southern California's cool-season precipitation, since in coastal southern California only about 2 per cent of the

Table 2 (from Lynch, 1931):

Table 2

RAINFALL INDICES, 1769-1930

Season	Los Angeles area	San Diego area
1769-70	155	......
1770-71	125	......
72	145	......
73	110	......
74	115	......
75	90	......
76	135	......
77	75	......
78	75	......
79	125	......
80	135	......
1780-81	125	......
82	55	......
83	65	......
84	115	......
85	110	......
86	75	......
87	90	......
88	75	......
89	135	......
90	100	......
1790-91	90	......
92	115	......
93	85	......
94	65	......
95	65	......
96	95	......
97	65	......
98	55	......
99	115	......
1800	85	......
1800-01	95	85
02	75	65
03	80	65
04	125	105
05	75	85
06	125	125
07	65	60
08	75	120
09	65	55
10	115	85

Season	Los Angeles area	San Diego area
1810-11	155	175
12	110	115
13	85	75
14	110	110
15	195	175
16	85	70
17	155	155
18	135	130
19	135	130
20	85	90
1820-21	145	150
22	65	110
23	65	65
24	65	70
25	220	180
26	45	60
27	65	70
28	75	85
29	35	40
30	75	100
1830-31	55	65
32	45	50
33	165	140
34	120	125
35	110	95
36	105	110
37	95	95
38	100	110
39	145	140
40	210	180
1840-41	40	45
42	145	135
43	65	70
44	45	50
45	65	65
46	70	70
47	135	130
48	110	110
49	75	80
50	135	130

Season	Los Angeles area	Santa Barbara area	San Diego area	San Bernardino area
1850-51	60	50	77	......
52	95	85	122	......
53	125	135	81	......
54	100	95	124	......
55	120	110	137	......
56	85	85	103	......
57	45	60	60	......
58	85	80	85	......
59	65	75	68	......
60	125	110	67	......
1860-61	90	85	101	......
62	220	200	168	......
63	40	50	43	......
64	50	45	56	......
65	95	95	88	......
66	110	105	130	......
67	135	135	141	......
68	140	147	115	......
69	110	92	120	......
70	55	60	56	50
1870-71	50	52	53	89
72	75	87	74	57
73	80	61	65	96
74	129	94	180	151
75	92	107	62	87
76	143	139	104	127
77	38	27	44	58
78	124	156	142	132
79	54	80	61	68
80	118	125	117	105
1880-81	71	80	85	71
82	69	70	86	67
83	68	70	75	47
84	240	233	234	228
85	61	71	80	75
86	147	113	154	107
87	90	88	74	66
88	118	129	110	108
89	134	117	129	127
90	206	193	156	158

Season	Los Angeles area	Santa Barbara area	San Diego area	San Bernardino area
1890-91	109	107	128	116
92	79	77	105	83
93	158	155	109	122
94	49	46	62	63
95	123	104	130	144
96	62	78	62	55
97	119	120	119	119
98	50	38	58	60
99	41	73	55	44
1900	64	70	68	62
1900-01	117	85	96	111
02	72	90	72	69
03	137	113	110	110
04	61	70	49	63
05	137	156	145	134
06	134	136	140	126
07	152	166	113	144
08	88	106	89	97
09	140	174	110	116
10	95	101	100	96
1910-11	121	182	99	115
12	82	76	95	91
13	81	75	69	68
14	163	185	108	150
15	120	121	152	132
16	131	132	155	149
17	100	109	95	116
18	92	121	86	86
19	66	69	77	74
20	97	73	106	113
1920-21	103	85	72	102
22	150	125	175	169
23	72	88	81	86
24	53	38	67	71
25	64	58	72	73
26	115	101	118	119
27	119	116	158	130
28	69	67	78	72
29	76	62	78	76
30	82	61	112	100

year's total rainfall normally occurs during the period June-September. These indices are also somewhat indicative of the cool-season precipitation in the interior southwestern United States, since correlation coefficients of monthly precipitation computed by the author for a 66-year period (see discussion by Pyke, 1966) between coastal southern California stations and interior desert and mountain stations as far away as eastern Arizona range between approximately +0.4 and +0.8 (values which are highly significant statistically), with the highest values generally occurring during late winter and early spring (the season of the normally greatest influence of warm equatorial ocean and accelerated Hadley Circulation conditions).

In Fig. 34 the average rainfall index for southern California (each year's arithmetic mean of the available area indices in Table 2) has been plotted for the period 1839-1840 to 1929-1930, superimposed upon the combined Berlage Southern Oscillation Indices and the other features of Fig. 32. An average rainfall index for southern California has been extended by the author forward to 1960-1961, using each year's per cent of long-term mean annual precipitation averaged over eight rainfall stations from Santa Barbara to near San Diego which have relatively homogeneous station records (little change in location or exposure--see discussion by Pyke, 1966).

Relationship Among Elements

The relationship between the average rainfall index for southern California and the Southern Oscillation Indices in Fig. 34 can be seen to be far from perfect. There is a somewhat better relationship between the values of the Southern Oscillation and the total-season quantities of southern California rainfall during the more recent decades than during the earlier portions of the period, but even during the latter 30 years the two elements would appear in many instances to vary independently of each other.

To demonstrate this quantitatively, correlation coefficients were computed by the author between the southern California rainfall indices (based upon season totals from July through June) and either the April-September or October-March series of Berlage's Southern Oscillation Indices. The computations were made for the entire 89-year period of record common to Lynch's rainfall indices (Table 2) and Berlage's Southern Oscillation Indices, 1841-1842 to 1929-1930, and for the 31-year period 1930-1931 to 1960-1961 common to Berlage's Southern Oscillation Indices and this author's average rainfall indices of eight southern California stations. The coefficients were computed for simultaneous pairings between rainfall and the October-March Southern Oscillation Index, and for correlations in which the rainfall lagged the October-March Southern Oscillation by 12 months or lagged the April-September Southern Oscillation by 6 or 18 months.

For the period 1930-1961 the coefficients turned out to be +0.42 for rainfall correlated with the contemporaneous October-March Southern Oscillation ($n = 30$ years), and +0.51 for rainfall correlated with the April-September Southern Oscillation of 6 months earlier ($n = 31$ years). If one assumes a normal distribution of the variables (probably a reasonably good assumption for the Southern Oscillation and a fair assumption for the rainfall), these results are statistically significant, especially for the +0.51 value, since the minimum significance levels are 0.36 ($n = 30$) and 0.35 ($n = 31$) for 95 per cent confidence and 0.46 ($n = 30$) and 0.45 ($n = 31$) for 99 per cent confidence (Hoel, 1962; Spiegel, 1961; and others).

For the 89-year period of Lynch's rainfall indices, taken as a whole, the correlation coefficients between the rainfall and the Southern Oscillation Indices (with lags from 0 to 18 months) were much smaller than those of the 1930-1961 period, ranging in this case from only +0.09 to +0.12. These values are well below the minimum 95 per cent significance level of 0.21 ($n = 89$). For the individual 29- or 30-year portions of this 89 years (1841-1870, 1870-1900, and 1900-1930) the computed correlation coefficients varied from +0.01 to +0.22--values well below minimum significance for $n = 29$ or 30.

The differences between the better correlations of the 1930-1961 period and the poorer ones of the earlier periods would appear likely to be due in a large part to random differences and sampling error, although some of this difference seems likely to be the result of fewer and less accurate items of data available during the earlier years upon which the indices of Table 2 and Fig. 34 were based.

The generally rather low values of the correlation coefficients computed here demonstrate that precipitation in the southwestern United States is dependent upon much more than merely the Southern Oscillation Indices of Berlage, based upon selected sea level pressure anomalies. The Southern Oscillation is only one imperfect indicator of equatorial Pacific Ocean temperature conditions, and (in a somewhat similar argument) a strong subtropical jet stream resulting from an equatorially induced acceleration of the Hadley Circulation is only one possible source of heavy precipitation in the southwestern

United States. One cannot obtain a true insight into the teleconnections (through the Hadley Circulation and subtropical jet stream) between warm equatorial Pacific Ocean anomalies and heavy precipitation patterns in the southwestern United States by merely overviewing the total spectrum of fluctuations of two of the elements which at times participate in this teleconnection chain. One must examine in detail (to the extent of the available data) each individual case of equatorial warming and the consequent anomalies in the atmospheric circulation and precipitation patterns.

Equatorial Warm Anomalies of 1904-1939

A detailed examination of Figs. 27-28 and 30-34 plus Table 1, along with the various other sources and types of available data mentioned above reveal that during the 35 years prior to 1939-1940, just as during the 35 years since, there appears to have been a significant--although by no means total--influence of warm equatorial Pacific Ocean anomalies upon the atmospheric circulation of the Northern Hemisphere, and some influence of these equatorial anomalies upon the cold-season precipitation of the southwestern United States. During each of the major equatorial warm periods between 1904 and 1939 there was a definite tendency--in some cases more pronounced and more persistent than others--for the development of a series of moderately intense cyclone waves, traveling eastward across the Pacific at middle or subtropical latitudes in a fast westerly flow--conditions very similar to those observed during each major equatorial warm-water anomaly from 1939-1942 since.

In some years, particularly from around January to March, these storms would reach eastward to the coast of California without curving substantially northward, and would give southern California and the rest of the southwestern United States considerably heavier than normal precipitation. This is especially noticeable during the seasons of 1904-1905 and 1913-1914, and to some extent, 1914-1915 (compare the southern California Rainfall and Southern Oscillation Indices of Fig. 34 for these years). During other seasons, however, such as the prominent equatorial warm-water and probable or definite El Niño years of 1911-1912, 1918-1919, 1925-1926, 1929-1930, and 1939-1940, the Pacific cyclones would usually curve northeastward a substantial distance off the coast and would very seldom break under a mean west coast high pressure cell; and as a result of this, the southwestern

United States remained considerably drier than normal throughout much of these seasons (see Fig. 34). (It was only toward the end of the 1911-1912 and 1925-1926 seasons that any very heavy precipitation fell in the far southwestern United States: in March of 1912 and in early April of 1926; and the March 1912 patterns were more of the high-amplitude type which will be discussed in a later section of this paper.) Even during the season of 1930-1931--the second season of the 1929-1932 equatorial warming--when (especially during January and early February) the weather maps over the eastern Pacific Ocean very much resembled those of 1940-1941, the precipitation over much of the southwestern United States averaged less than normal, as the storms involved were somewhat weaker and the pattern considerably less persistent (in 1930-1931) than in 1940-1941.

Thus it is obvious that not every period of warm equatorial ocean conditions (implied by high equatorial Pacific island rainfall and high (Berlage) or low (Walker) values of the Southern Oscillation Indices) is causally associated with an abnormally high cool-season precipitation total in the southwestern United States (a fact already seen in Fig. 34 and from the correlation coefficients of rainfall vs. Southern Oscillation). In some cases the equatorial influence is of too short a duration to substantially contribute toward an excess in a rainfall year's total precipitation. At other times the longitude span of the equatorially enhanced subtropical jet stream does not quite reach to the southwestern United States. (This often tends to occur during the somewhat weaker equatorial warm anomalies, when warmer ocean conditions and enhanced convective activity will occur over the western portions of the eastern equatorial Pacific Ocean, but with the cool-water dry tongue continuing to exist over the more eastern parts of the equatorial belt.)

Therefore, although a number of equatorial warm-water seasons have also been seasons of at least somewhat heavier than normal precipitation in the southwestern United States, there have also been several in which the Southwest has remained relatively dry (see Fig. 34). There have also been during the historical record a number of seasons of abnormally cool equatorial oceans during which parts or all of the southwestern United States experienced very heavy precipitation--often with severe flooding. These conditions will be discussed in later sections of this paper.

Equatorial Warmings Prior to 1904

The charts of Allison et al.--Figs. 28 and 30--date back to only 1904 and 1905 respectively. Prior to 1904 there are no readily available 12-month running means of equatorial Pacific island rainfall, and prior to 1896 (the earliest tabulation of this parameter by Quinn and Burt--Table 1), no useful information at all about equatorial Pacific rainfall. The end of the 19th Century also marks the earliest available regular publishing of several other meteorological elements, including the fully analyzed daily synoptic weather maps for the Northern Hemisphere (U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.): 1899, and daily precipitation data for the United States (U. S. Weather Bureau, ESSA, and NOAA, 1897 et seq.): 1897. Prior to this time, as was noted earlier, monthly precipitation for U. S. stations is published by the U. S. Weather Bureau (1931 ff), which, along with McAdie (1903), also list certain additional precipitation statistics for selected stations. Some unpublished daily precipitation values are on file at the National Climatic Center, Asheville, North Carolina, as well as in certain State and local climatological offices. A limited number of daily rainfall values for some of the more prominent historical storms are tabulated by U. S. Weather Bureau (1943), Weaver (1962), U. S. Corps of Engineers (1940 ff), Ludlum (1970-1972), and others. A set of weather maps with limited data and very limited and primitive analyses is printed for the continental United States (no oceanic coverage and sometimes very limited coverage west of the Rockies) by the U. S. Signal Service (1870-1891) and by various U. S. Weather Bureau forecast offices. Mean sea level pressure and cyclone trajectory charts made from these individual maps are published in Monthly Weather Review. A few more recently analyzed daily sea level pressure and surface weather charts for selected outstanding storm events are also included in U. S. Weather Bureau (1943), Weaver (1962), and others.

All of these data become more sparse and sketchy, however, during the earlier years, and prior to about 1870 one must rely almost exclusively upon the rainfall and Southern Oscillation indices of Lynch and Berlage respectively, except for whatever miscellaneous data tabulations and historical accounts of individual storms, months, or season happen to be available (see references in later sections under discussions of individual cases). Even these Lynch and Berlage indices become less reliable with decreasing time, though, as the data base upon which each of these indices is constructed "thins out" (see, e. g., Table 2), and in the case of Lynch, becomes more qualitative and indirect (e. g., crop harvests and accounts of floods and droughts instead of direct precipitation measurement). Despite these difficulties, there are a number of points that can be noted about equatorial warm anomalies and precipitation in the southwestern United States during these earlier years:

Figs. 31-34 and Table 1 indicate the occurrences of rather prominent and extensive equatorial warmings in 1899-1900 and 1902-1903, with possibly El Niño conditions in 1899. The daily synoptic weather maps (U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.) and the precipitation records for those years, however, indicate even more high pressure and drier conditions than usual during 1899-1900 and part of 1902-1903. It was only during March 1903 that a pattern somewhat resembling those of other warm equatorial Pacific Ocean years developed strongly enough to result in heavy precipitation in southern California and portions of other Southwest States.

Although the equatorial warm anomalies prior to 1899 (inferred by high values of Berlage's Southern Oscillation Indices and citings of El Niño occurrences by Frijlinck (1925)--see Fig. 34) predate the published Northern Hemisphere daily synoptic weather maps (U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.), so that only sketchy information can be gained as to the types of atmospheric circulation patterns effected during most of those years, it can nevertheless be noted from Fig. 34 and from the published monthly rainfall data (U. S. Weather Bureau, 1931 ff) that precipitation in southern California and Arizona, as well as parts of Nevada, Utah, Colorado, and New Mexico, did tend to at least exceed normal during most of these equatorial warmings, especially in the winter and early spring months. Such appears to have been the case during the warm-water (and in some cases, El Niño) seasons of 1896-1897, 1890-1891(EN), 1888-1889, 1887-1888, 1885-1886, 1883-1884(EN), 1877-1878(EN), 1873-1874, and perhaps in certain earlier years, but not during the years of 1884-1885, 1880-1881, or 1876-1877(EN), when total seasonal precipitation averaged below normal in most areas. Even during these drier years, however, precipitation averaged above normal--sometimes substantially above normal--for certain months of certain years, such as December 1884 (the entire Southwest), March 1881 (mostly Arizona), December 1880 (the entire Southwest except the lower deserts), February 1877 (eastern Arizona), January 1877 (mostly southerly California and Nevada), and several other months (in localized areas).

Although (as has been mentioned earlier) only very crude weather maps with limited analyses are available for these early years, one special set of recently analyzed daily sea level charts prepared by the U. S. Weather Bureau (Weaver, 1962) for the very wet period of 18-25 December 1884 over the far western United States and the extreme eastern Pacific Ocean shows a storm series pattern very similar to those seen in other winters of warm equatorial ocean anomalies.

Among the seasons of heavy southwest United States rainfall prior to 1900 that occurred around the times of major equatorial warm anomalies, three are historically quite outstanding. The first in this series is the season 1883-1884. Although the Southern Oscillation Indices of Berlage (e. g., Fig. 34) and Walker (Fig. 33) do not show a particularly prominent deviation from the mean during that period (only a moderate departure from 1883 to 1886), the year 1884 is indicated as one of El Niño by Frijlinck (1925)--see Fig. 34. That season was also one of extremely heavy precipitation over all of the southwestern United States--the greatest on record (before or since that year) at a great many stations. The entire period December 1883 through April 1884, and particularly the months of February and March, witnessed the movement across the southwestern United States of an unprecedented series of Pacific storms that dropped moderate to heavy precipitation over the entire region in an almost endless barrage. Each of these months was characterized by a large number of days with moderate or heavy precipitation (although no truly extreme 24-hour amounts), moderate temperatures, and very large monthly rainfall totals, with great accumulations of snow over the high elevations (U. S. Weather Bureau, 1931ff; McAdie, 1903; U. S. Corps of Engineers, 1940ff; Ludlum, 1970-1972; and others). Heavy runoff occurred in many areas from the accumulated rainfall and the resulting saturated soil conditions, and the melting of mountain snow packs during the late spring of that year led to the greatest floods of record along portions of the Colorado River (Smith and Heckler, 1955). All of these hydrometeorological characteristics, plus the sketchy patterns which can be seen in the weather maps of U. S. Signal Service (1870-1891) and Monthly Weather Review, definitely suggest that the season of 1883-1884 was perhaps meteorologically more like that of 1940-1941--and likely even more intense--than anything before or since.

The month of August 1883 also saw the eruption of the volcano Krakatoa in the South Pacific, and many meteorologists (including Berlage, 1966) have linked the unusual weather of the following Northern Hemisphere winter to the effects of this eruption. It is not argued here one way or the other as to whether Krakatoa may have contributed (through changes in the earth's radiative balance, the addition of precipitation nuclei, etc.) directly or indirectly to abnormalities in the Northern Hemisphere weather patterns--perhaps, as Berlage and others feel, even to the point of initiating large-scale circulation changes, including a weakening of the trade winds, which could have in turn triggered or accelerated an equatorial warming. It does appear probable, though, that whatever were the causes of its initiation, a warmer than normal equatorial Pacific Ocean and the associated anomalies in the Hadley Circulation and subtropical jet stream are very likely to have exerted a considerable influence upon the unusual precipitation patterns of the southwestern United States during 1883-1884.

1984 update: In late 1982 another major El Niño condition developed. The subsequent Northern Hemisphere winter followed the patterns of 1883-84, 1940-41, 1957-58, 1972-73, and other similar years, and in fact was perhaps the most severe of its type in the past 100 to 150 years.

This major El Niño followed by several months the eruption of the volcano El Chichón in southern Mexico, Mar-Apr 1982--an eruption that spread large quantities of volcanic dust and gases around the globe, particularly in the tropical belt, reducing insolation by more than 10% in many low-latitude regions.

It has been debated by numerous meteorologists and climatologists whether this volcanic eruption and the changes in radiative balance that appear to have resulted did or did not cause or intensify the subsequent El Niño.

In my own opinion, it appears that the 1982-83 El Niño was already in the developmental stages when El Chichón erupted, and that it would have occurred even without the volcanic eruption. It does, however, appear that this El Niño was likely intensified by the presence of the volcanic dust, in the following manner:

As the high-altitude dust spread around the tropical belt, reducing insolation, the "Maritime Continent" region of Indonesia (a term used by Prof. Ramage of University of Hawaii), which is the thunderstorm capital of the world, began to see a marked reduction of convective precipitation--most likely as the result of the reduced sunlight. The oceanic portions of the equatorial belt, to the east and west of Indonesia, would have been less directly affected by the reduced insolation.

As a pronounced drought developed over Indonesia in conjunction with a large-scale reduction of the upward mean vertical motion over that region, the entire Walker Circulation from South America westward to Indonesia weakened and perhaps even reversed. The result was a major warming of the eastern equatorial Pacific Ocean--by more than 5 degrees Celsius over large areas in November and December 1982.

It now appears in retrospect that the relatively strong El Niño of 1883-84 was likely intensified as the result of the volcanic dust from the eruption of Krakatoa in August 1883. The fact that Krakatoa is located adjacent to the Indonesian "Maritime Continent" further increases the likelihood that this region experienced the greatest insolation-reducing effects from the eruption.

It would seem that any major volcanic eruption in the future--one that puts large quantities of dust and gases high into the stratosphere--could affect the Walker Circulation. If such an eruption should occur in the tropics, especially in the Indonesian region, during the incipient phases of an already occurring El Niño, then it would appear likely that such an El Niño could be significantly intensified.

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The other two noteworthy seasons in this trio are those of 1889-1890 and 1890-1891. These back-to-back seasons climaxed a generally wetter than normal period in the southwestern United States that began in early 1887--a period which, as one can see in Figs. 31-34, was spiked by two prominent equatorial warm anomalies (implied by sharp peaks (troughs) in the Berlage (Walker) Southern Oscillation Indices), one during 1888-1889 and the other in 1891 (this latter year also being one of extreme El Niño conditions). These peaks were separated by an extremely well-marked and very sharp reversal of the Southern Oscillation (and presumably equatorial ocean temperatures) in 1889-1890.

After well above normal precipitation in the southwestern United States during March of 1889, and even a summer with abundant rainfall at a number of stations (see discussion in a later section of this paper), the fall and early winter of 1889-1890 brought extremely heavy precipitation to many areas of the Southwest, with the wettest October-January in history in coastal southern California, where December 1889 still stands as the month of all-time greatest rainfall at a number of stations.

It is interesting to note that this great excess of rainfall in the southwestern United States occurred not during either of the two major peaks of equatorial ocean temperature, but close to the climax of the prominent reversal sandwiched between these peaks (see Fig. 34). This rather unusual timing of this outstanding precipitation anomaly will be discussed later in this paper.

Although the season of 1890-1891 experienced several months of greater than normal precipitation at a number of stations in the southwestern United States, it was the month of February 1891 which stands out as one of extremely heavy rainfall throughout most of the Southwest, especially in the mountainous areas. Widespread flooding occurred on many of the larger rivers as the result of the heavy rain and melting snow during February 1891 (Smith and Heckler, 1955; and others), and the flow on the Gila River as it entered the Colorado River was so extreme (by far the greatest ever recorded) that the town of Yuma, Arizona was almost completely wiped out, according to newspapers and other accounts (see, e. g., Ludlum, 1970-1972).

It is interesting to note that although the 1890-1891 spike in the Southern Oscillation curves of Berlage and Walker (Figs. 31-34) does not appear to be nearly as prominent as the one in 1877, or even as prominent as its immediate predecessor of 1888-1889 or some of the peaks between 1900 and 1915, the accounts of Schott (1931) and Eguiguren (1894) indicate that the intensity and extent of the equatorial Pacific Ocean warming and El Niño rainfall along the South American west coast of early 1891 were likely to be among the very greatest, if not the greatest, of all time--equalling or even surpassing those of 1939-1941, according to Bjerknes (1961).

COMPARISON OF ATMOSPHERIC PATTERNS RESPONSIBLE FOR HEAVY PRECIPITATION

Of course, as was discussed earlier, and as can be seen from Fig. 34 and from the correlation coefficients between the rainfall and Southern Oscillation indices, not all heavy precipitation observed in the southwestern United States results directly or indirectly from conditions of anomalously warm equatorial Pacific Ocean water. There have been many historical cases in which very heavy precipitation has occurred in portions of the Southwest during periods of cooler, or even much cooler, than normal equatorial Pacific water, such as in 1861-1862, 1889-1890, 1892-1893, 1906-1907, 1915-1916, 1921-1922, 1926-1927, 1933-1934, 1936-1937, 1937-1938, 1955-1956, and 1961-1962. The main theme of the preceding sections of this paper concerns not so much the total quantities of precipitation in the southwestern United States, but the type of storm pattern which usually tends to occur (and can be expected to occur) during years of abnormally warm equatorial Pacific waters, namely, the strong subtropical jet stream across the eastern Pacific and southwestern North America, which tends to propel and direct Pacific cyclone disturbances across the southwestern United States at frequent intervals, bringing extended periods of recurrent rainfall to the region.

Blocking Highs in the Northeastern Pacific

By way of contrast to the atmospheric and precipitation anomalies induced by prominent warm equatorial ocean anomalies, it appears that those atmospheric regimes which result in heavy precipitation in the southwestern United States during periods of normal or cooler than normal equatorial seas, or even during periods of weaker equatorial ocean warmings, more often than not tend to be of the high-amplitude, blocking high and cold low type, in which storms either drop down the Pacific Coast from the north and intensify within a few degrees longitude of the coastline (offshore or onshore), or else break under a high-amplitude northeastern Pacific blocking high and approach southern California from out of the southwest, or both (resulting in a major storm combination along or off the California coast or a short distance inland).

When the eastern equatorial Pacific Ocean is relatively cool, and the Hadley Circulation over this span of longitudes is thus relatively weak, one could perhaps be tempted to argue that the Northern Hemisphere subtropical and mid-latitude atmospheric circulation becomes essentially decoupled from the forcing mechanisms of the deep tropics and is therefore no longer restricted to a strong quasi-zonal subtropical jet stream pattern. This decoupled circulation would be somewhat more free to meander into various low- and high-amplitude ridge-trough patterns, forced or at least guided by sea surface temperature anomalies in the north Pacific Ocean, as well as perhaps by continental land surface anomalies, such as snow cover (see articles by Namias, 1963, 1965, 1969a, 1969b, 1970, 1971, 1972, 1973b, and many others--articles also published in Namias, 1975).

This argument, although perhaps partially true, is probably somewhat oversimplified, however. The Northern Hemisphere atmospheric circulation is in actuality acted upon at all times by a multitude of internal and external sources (not, however, to be confused with a multitude of <u>extraterrestrial</u> sources!). These sources of influence range in latitude from the equatorial oceans and continents (around the entire globe) to the polar ice caps (of both hemispheres); and for long-term effects, none of these sources can be totally ignored. Thus it is very likely that even during seasons of pronounced equatorial warmings, such as those of 1940-1941, 1957-1958, 1972-1973, and probably 1883-1884 and 1890-1891, the ocean temperature patterns in the subtropical and mid-latitude North Pacific, as well as the land surface conditions of North America and other continents, must have exerted a considerable influence upon the atmosphere and are likely to have contributed very significantly to the differences (discussed earlier in this paper) in the positions and amplitudes of the mean monthly long-wave ridges and troughs observed among the corresponding months of these various warm-equator seasons (see Namias, 1959, 1974).

Conversely, during the so-called cool equatorial Pacific years--years in which the sea surface temperatures are below normal over the <u>eastern</u> equatorial Pacific belt (out to approximately the International Date Line)--there is still very likely--probably more likely than ever--to be (during the Northern Hemisphere winter) a major contribution to the Hadley Circulation and the Northern Hemisphere subtropical jet stream over the longitude span of the <u>western</u> Pacific (Ramage, 1968; Quinn, 1972). During seasons of cool eastern equatorial Pacific waters and increased atmospheric subsidence over the equator in these longitudes, there is a stronger and more extensive east-to-west Walker

Circulation and a correspondingly more intense and extensive field of rising air over the "maritime continent" (as termed by Ramage) at the western end of the equatorial Pacific.

It is noted by Ramage (1968), in comparing the two contrasting regimes of January 1963 and January 1964, that during the strong Walker Circulation (and cool eastern equatorial Pacific) period of January 1963 (compare Figs. 23-26 and 29), the extensive rising motion over the maritime continent resulted (through Hadley Cell coupling) in an exceptionally strong subtropical jet stream over the western north Pacific Ocean--a jet which was, according to Ramage, hydrodynamically unstable on its southern side. It is hypothesized by Ramage (1968)--an argument also cited and supported by Quinn (1972)--that this strong jet and its hydrodynamic instability may have very well led to the formation and persistence of a strong blocking high in the eastern Pacific that winter--a high which had major downstream consequences over the United States: significantly below normal temperatures over a very large area from the Rockies to the Appalachians, especially during January (see also Namias, 1963; MWR Apr 1963; Ludlum, 1970-1972). Quinn (1972) also cites and discusses other winters in which a very strong mean blocking high in the northeastern Pacific sent unusually cold air southward into western or central North America: 1915-1916, 1916-1917, 1948-1949, 1949-1950, 1956-1957, and 1968-1969. Quinn notes that these winters all occurred either during, or within a few months of the beginning or ending of, a prominent eastern equatorial Pacific cool period and extensive equatorial Pacific island drought.

It would appear that one possible aspect of this hydrodynamic instability of the western Pacific subtropical jet stream might be the development of a "Hadley Anticyclone" (see Bjerknes, 1969b, and earlier discussions in this paper) to the south of this jet as the result of the heat input from the equatorial maritime continent. This would impart an anticyclonic curvature to the jet, and could quite likely result in the formation and maintenance of a downstream subtropical trough or closed low somewhere between the eastern Hawaiian Islands and approximately Midway Island--a Kona type low, which would serve as an "anchor" low for the northeastern Pacific blocking high through both barotropic and baroclinic effects (e. g., constant absolute vorticity trajectory considerations, and the northward transport and release of large quantities of sensible and latent heat from the tropics) (see Namias, 1971; Pyke, 1972--Sec. III.C.1.).

In addition, it is shown by Allison et al. (1972) that the ocean temperatures in the eastern equatorial Pacific are very well correlated with the ocean temperatures in the 5-15N latitude belt over these same longitudes (a correlation coefficient of +0.79, with the 5-15N belt lagging behind the equatorial zone by 1 month), and quite well correlated with those in the 10-20N belt (+0.63, with the 10-20N belt lagging behind the equatorial zone by 3 months). Therefore a positive sea surface temperature anomaly in the eastern equatorial Pacific zone would likely be associated with--probably causally connected with--a positive ocean temperature anomaly in the latitudes of 10-20N, and especially 5-15N, over these same longitudes. Some of the reasons for this connection, including the role of the North Equatorial Countercurrent, have been discussed by a number of authors, including Bjerknes (1961, 1966b, 1974b), Wyrtki (1973), Namias (1973c), Krueger and Winston (1975), and others (see also discussion of this topic later in this paper). One can see this general interlatitude relationship in Fig. 29 by a comparison of the Pacific Ocean temperature fluctuations among the various latitude belts.

One can also see in Fig. 29 (as is discussed and illustrated by Bjerknes, 1969c) that the interannual sea surface temperature fluctuations in the non-equatorial tropical belts are normally considerably smaller than those along the equator. This can be further seen in Figs. 35 and 36 (reproduced from Laviolette and Seim, 1969) by a comparison of the maximum and minimum Pacific Ocean temperature charts for a given month of the year (e. g., the month of February in Figs. 35-36). It can be seen in Fig. 35 that when the equatorial ocean is abnormally warm, there is usually rather little difference between the sea temperatures in the belt 5N-5S and those in the belt 5-15N over the longitude band from approximately 120 to 170W (this is generally true during the months of January through May, according to Fig. 35 and the other maximum temperature charts of Laviolette and Seim, 1969). When the equatorial ocean, however, is near normal, or especially when it is cooler than normal (e. g., Fig. 36), then the difference between the temperatures of the 5N-5S and 5-15N belts become very considerable (with the equatorial belt several degrees cooler).

In Fig. 29 one can see furthermore that the shapes of the curves in the various latitude belts are not the same.[1] In the equatorial latitudes the major peaks tend to occur considerably

[1] Note: Do not compare the latitudinal differences in Fig. 30, since this figure represents <u>derived</u> sea surface temperature curves (Allison et al., 1972). In these derived curves the <u>amplitudes</u> vary among the latitude belts (based upon the standard deviations of amplitudes in each belt), and the phases may differ (based upon the lag times computed by Allison et al.). The shapes of the various curves, however, remain similar by derivation.

earlier (much more so than merely the 1-3 months of the Allison et al. correlation lags), and the cooling in the equatorial belt is significantly more rapid than in the higher tropical latitudes--a cooling which is likely accelerated in the equatorial zone by the rather rapid onset of surface divergence and upwelling which develops over a great portion of the eastern equatorial Pacific in response to any increase and northward expansion of the Southern Hemisphere trade winds. It can thus be seen that as the temperatures of the equatorial ocean belt, following a significant peak, are beginning to decline rather rapidly, the temperatures of the 5-15N and 10-20N belts are often just reaching their maximum.

Hence, because of the factors discussed in the paragraphs above, it appears very likely that beginning quite shortly after the peak of a significant warm anomaly in the eastern equatorial Pacific Ocean, the temperatures of the equatorial belt (5N-5S latitude) will become significantly lower than those between 5 and 15N. As a result of this, the intertropical convergence activity should tend to quite rapidly shift away from the equatorial zone toward the warmer water between 5 and 15N (and occasionally even between 15 and 20N), and would likely remain in these latitudes throughout the cooling phase and any subsequent period of negative temperature anomalies.

This major belt of convective activity would likely now be far enough north to directly interact with any Kona lows which might develop near the latitudes of the Hawaiian Islands, and would likely reinforce such Kona lows and supply additional sensible and latent heat to the northward-streaming air along the eastern sides of these "anchor" lows--thus in turn serving to further build and maintain blocking highs in the northeastern Pacific (see also discussion by the author: Pyke, 1972--Sec. III.C.1.).

Thus it can be seen that any argument stating that the atmospheric circulation over the eastern north Pacific tends to become essentially decoupled from equatorial latitude influences during periods of cooler than normal eastern equatorial Pacific waters does appear to be oversimplified. The positions, intensities, and persistence of high-amplitude blocking highs in the northeastern Pacific that frequently tend to occur during such equatorial coolings may indeed be governed in part by teleconnections not only from the eastern low-latitude Pacific Ocean but from portions of the Pacific more than a third of a global circumference upstream.

It should be noted, however, that even if all of the arguments concerning the teleconnections from the eastern and western equatorial Pacific Ocean--during both warm and cool water periods--happen to be true, however, the contributions from the subtropical and mid-latitude northeastern Pacific Ocean toward the building and maintenance of a mean northeastern Pacific blocking high, and especially toward the latitudinal and longitudinal positioning and the configuration of such a high, are likely also to be very important--and probably more important--than those contributions from either the eastern or western equatorial Pacific. The relationships between north Pacific Ocean surface temperatures and the overlying and downstream atmospheric circulation, as discussed by Dr. J. Namias (in a great many articles), must be very seriously considered in the evaluation of any historical anomalies in Northern Hemisphere weather patterns, as well as in any attempts to prepare monthly or seasonal outlooks.

Location and Configuration of Blocking Highs

Sinch high-amplitude and blocking atmospheric patterns can occur over rather wide ranges of latitudes and longitudes and can assume any number of different configurations (depending to a great extent upon the distributions of prevailing sea surface temperature patterns), the precipitation and air temperature regimes in the southwestern United States resulting from such high-amplitude patterns can range all the way from very wet to very dry, and from much warmer to much colder than normal.

If a large, persistent high happens to be located over the west coast of the United States or slightly inland, the southwestern United States will remain dry to very dry, usually with above normal temperatures, while the more eastern parts of the nation will be colder than normal. If the high is located just off the coast and is of high amplitude but not in a well-marked omega-shaped blocking configuration (with a well-developed trough or closed low to its southeast), then the western and central United States, and perhaps the eastern States as well, will be considerably colder than normal, but with the western regions still remaining quite dry (see, e. g., the January 1963 case--Namias, 1963; Quinn, 1972; MWR Apr 1963). If the position and configuration of the high are such that a significant downstream trough or low can form over the southwestern United States or offshore, or if a low-latitude storm track can break under the blocking high and reach the west coast of the United States, then the Southwest will be significantly wetter than normal.

A discussion of selected types and configurations of the heavier precipitation-producing high-amplitude regimes, the sea surface temperature anomalies which tend to be associated with these regimes, and the resulting precipitation distributions over the southwestern United States can be found in another paper by the author (Pyke, 1972--Sec. III.C.). The hydrologic significance of the various heavy precipitation-producing high-amplitude atmospheric patterns, as well as of the warm-equator-generated strong subtropical jet stream pattern, is discussed in the next several sections.

Hydrologic Aspects of Heavy Precipitation Patterns

Although there is a multiple spectrum of precipitation patterns and hydrologic conditions which can occur in any given region (precipitation type, intensity, duration, and areal extent; dry, wet, or frozen ground; amount, depth, water content, and condition of snow cover; etc.), the types of storms and ground conditions experienced in the southwestern United States during the greater winter rainfall season can generally be categorized into several basic regimes. Only those regimes capable of producing heavy precipitation or resulting in heavy runoff are discussed here.

(1) Recurrent storms of moderate temperature. This is the type of storm pattern most frequently associated with warm equatorial Pacific Ocean anomalies and a persistent, strong subtropical jet stream across the eastern Pacific Ocean and the extreme southern United States (as in 1940-1941, 1957-1958, and 1972-1973, plus a number of other seasons). During these regimes a persistent train of low- to mid-latitude cyclones will develop and travel eastward across the north Pacific Ocean. These cyclones, guided by the subtropical jet stream, will move onshore and march across the southwestern United States at frequent intervals, each dropping moderate to at times heavy precipitation over large areas, with snow levels of generally moderate elevations (approximately 5000-7000 feet above sea level).

Storms of this type are usually directly beneficial to agriculture and to urban and rural ground water supplies through repeated periods of infiltration, although at times the pattern can become too persistent for many crops, especially during the latter months of the fall-winter-spring rainfall season. This type of storm pattern is also beneficial to urban and rural water supplies through the filling of water conservation reservoirs because of the repeated moderate runoff which generally results from this type of storm series, as well as from the large snow packs which normally accumulate in the higher elevations--snow which later melts and runs off.

Because of the relative zonality of the subtropical jet stream and associated cyclone track (i. e., a nearly west-to-east path of movement), the storms of this type tend to be of moderate moisture content (when compared to storms that approach the southwestern United States from considerably lower latitudes). Also, because of the high speed of the subtropical jet stream and the consequently high speed of movement of the individual cyclones of this type of storm pattern, the rainfall from such a storm at any given location, although frequently heavy at times during the storm period, will generally not last for more than a day or so at the most, and will then let up for some time--allowing things to dry out somewhat--before the next cyclone wave moves in. For these reasons, therefore, there is not too often much serious flooding experienced on the smaller or intermediate-sized rivers from individual storms associated with this warm equatorial ocean type of atmospheric regime. (Some moderately severe floods have occurred in certain smaller watersheds from accumulations of rainfall, such as the southern California floods of 1884, 1891, and 1914; and some floods have also occurred on small watersheds during such years from intense local convective storms embedded within general storms--see, e. g., Table 3.) Severe flooding on larger river systems, however, can at times develop--usually after a prolonged period of recurring rainfall, often toward the end of a rainfall season of this type (i. e., late winter or spring)--from the general accumulation of this rainfall and from the melting of snow packs. This flooding can be aggravated on certain river systems by the filling to capacity of reservoirs (which can sometimes be hastened through the lower usage of irrigation water by farmers who have benefitted directly from the recurrent rainfall).

Some of the major historical floods that have occurred on large river systems from persistent storm patterns of this warm equatorial ocean type include those of the Colorado and Gila Rivers in 1884 and 1891, the flooding in the southwestern and south central United States during May 1957, and the disastrous floods on the Mississippi River during the spring of 1973 (all discussed earlier in this paper), plus some marginal situations (with potential serious flood threats) in Arizona and California in 1940, 1941, 1966, 1973, and other years which resulted from the filling to very near capacity of a number of reservoirs and reservoir systems.

(2) Cold, moderate to heavy storms. This type of storm pattern results exclusively from high-amplitude atmospheric regimes in which a large high pressure ridge lies a short distance offshore and a deep cold trough or cut-off low is located near the California coast or just slightly inland. Storms of this type often drop moderate to heavy snow over large areas down to low levels (2000-4000 feet above sea level, and at times even lower). This is the type of regime which prevailed from December 1915 through much of January 1916

(Quinn, 1972; Ludlum, 1970-1972; and others), and appears to have been an open trough pattern into which dropped a number of major Pacific storms (U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.). Probably the most outstanding example of a deep and persistently recurring cut-off type of low over the far southwestern United States, resulting from a classic omega-shaped blocking high in the eastern Pacific, occurred during January 1949 (U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.; Klein, 1949; Quinn, 1972; Rosenthal, 1972; Ludlum, 1970-1972; and others). Other examples of this general type of cold storm pattern include the months, or portions of the months, of December 1856(?), December 1861 - January 1862, February 1867(?), January 1868(?), January 1882(?), February 1887(?), January 1888, January-February 1890, January 1895(?), January 1898(?), February 1901, January 1907, March 1912, January-February-March 1922, December 1924, December 1932, January 1937, February 1944, December 1951 - January 1952 and March 1952, January 1957, February 1959, January 1962, and December 1967 (U. S. Weather Bureau, 1931 ff, 1943, 1953 ff, 1964-1965; U. S. Weather Bureau, ESSA, and NOAA, 1897 et seq.; U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.; Quinn, 1972; Roden, 1966; Ludlum, 1968b, 1970-1972, 1973; MWR; and others).

If this type of storm pattern persists or recurs over a large portion of a season, the eventual melting of the accumulated snow packs will often provide large volumes of runoff for water conservation reservoirs, and in some cases may result in flooding on the larger river systems, just as can occur with the recurrent moderate-temperature type of storm pattern discussed in (1) above.

(3) Warm, heavy storms--coherent atmospheric flow pattern. If the cold low of a high-amplitude regime (of the type discussed in (2) above) should develop a significant distance off the California coast, or should retrograde to such a position, then the air moving into the southwestern United States from around this low will be warmer and more moist than in the cold storm type discussed above. In this warmer type of storm pattern, snow levels can often rise to 6000-8000 feet, and larger proportions of incident precipitation will run off instead of remaining on the ground as snow. If this pattern should persist for a large number of days, an almost continuous train of storm impulses can assault the southwestern United States, bringing moderate to heavy precipitation in an almost unceasing barrage. Flooding can occur on many river systems of moderate size from the effects of the heavy rain; and if this type of regime has evolved through a retrogression of a persistent cold, heavy storm

pattern, then the melting of large quantities of snow in the low and intermediate elevations can greatly add to the flood problem.

This type of regime has developed many times during the period of historical records. Some of the more outstanding cases of this storm type include those of December 1866, April 1880, November 1902, November 1905, December 1906, December 1908, January 1916, October 1916, April 1917, February-March 1918, November 1919, December 1921, January 1935, October 1946, January 1952, March 1954, October 1959, and February 1969. The January 1916 and January 1952 cases are ones which evolved from out of a cold storm pattern (see above) to a warm storm type through retrogression of the mean long wave trough to a position off the coast (see MWR Jan 1952; and Carr, 1952, for descriptions and discussions of the 1952 regimes).

(4) Very warm, very heavy storms--split atmospheric flow pattern. Even more potentially disastrous than the single high-amplitude ridge and trough pattern is a regime in which a large high-amplitude ridge over far western Canada or in the eastern or central north Pacific cuts off at high latitudes and allows a storm or series of storms to break under the high at low or very low latitudes and travel toward the California coast, sometimes linking up with the flow coming southward around the eastern edge of the high and causing an explosive baroclinic cyclone intensification near or a short distance off the California coast. The potential exists in this type of storm pattern for extremely heavy, warm rains (snow levels 8000-11,000 feet or above), persisting over periods of several days to a week or more. Severe and widespread flooding and mudslides frequently result.

Fig. 19a (reproduced from MWR Apr 1969) shows the mean monthly 700 mb height configuration for January 1969. This was a month during which perhaps the most outstanding case of this very warm and very heavy type of storm regime occurred (see Bonner et al., 1971; Namias, 1971; Rosenthal, 1972; MWR Apr 1969; Weatherwise Apr 1969). Figs. 19c-f (reproduced from Bonner et al., 1971) depict satellite mosaics and meteorological analyses (fronts, jet streams, 500 mb height configurations, etc.) for 23 and 24 January 1969. These figures represent a sample of the patterns that occurred throughout nearly the entire latter half of this month, as an extended series of cyclones continually broke under the large, persistent blocking high in the north central Pacific and plunged to exceptionally low latitudes, thereby tapping great quantities of tropical moisture from the intertropical convergence zone and advecting this moisture directly into central and southern California. As a result of this, many stations in the southwestern United States, especially in southern California, experienced unprecedented 7- to 12-day rainfall totals (see Fig. 19b, reproduced from Weatherwise Apr 1969; see also Simpson, 1969; Bonner et al., 1971; U. S. Weather Bureau, ESSA, and NOAA, 1897 et seq., 1951 et seq.; Ludlum, 1970-1972; and others); and perhaps the most widespread and severe flooding in the history of southern California was prevented only by the presence of modern federal, State, and local flood control systems.

Another case of very warm, very heavy rainfall in southern California resulting from a split in the mid-latitude atmospheric flow regime, occurred in late January 1956, when a weather map configuration very similar to that of January 1969 (Fig. 19a) developed (see MWR Jan 1956; Helvey, 1966). The rain storm which struck southern California on 25 and 26 January of 1956 was equally as intense over some low-elevation areas as was any part of the January 1969 storm series; but it did not last nearly as long as the 1969 siege and was not as heavy in the higher elevations, and consequently resulted in much less severe and much less widespread flooding.

The patterns of late January 1956 were an outgrowth of those of the previous month (December 1955)--a month in which the low-latitude trough in the eastern Pacific was even sharper, with the southwesterly flow on its eastern side traveling farther northward, than in January 1956 or January 1969 (Figs. 19a,d,f)--a pattern which brought record-breaking rainfall and flooding to a large portion of northern California (California Department of Public Works, 1956; MWR Dec 1955; Cole and Scanlon, 1955; Weaver, 1962; Ludlum, 1970-1972). Another meteorological pattern of this type, and one very similar to that of December 1955, occurred in December 1964, when again a split flow across the Pacific resulted in extremely heavy rainfall and flooding in northern California, as well as in parts of Oregon (MWR Mar 1965; Ludlum, 1970-1972). Still other, but less intense, regimes of this type affected northern California in November 1950 (Weaver, 1962; Ludlum, 1970-1972; MWR Nov 1950) and in January-February 1963.

Other historical cases where heavy storms or storm series have hit southern California and other parts of the southwestern United States from out of the west of west-southwest, sometimes combining with storms from out of the north or northwest, include those of January and March 1906, January 1909, March 1912, February 1913, January-February 1915, March 1918, February 1927, December 1933 - January 1934, February 1937, December 1937, February-March 1938, January and March 1943, January and February 1954, February 1962, mid-February 1963, and December 1966 (U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.; U. S. Weather Bureau, 1943; Weaver, 1962; MWR May 1962, May 1963, and Mar 1967; and others).

(5) Cold storms followed by very warm, very heavy storms. Of course the ultimate in flood potential (at least that which could result from winter-type storms) would probably occur if a long sequence of cold, heavy storms, caused by a high-amplitude blocking high offshore and a deep cold low near the California coast, were to be followed by a series of intense, warm storms which had broken under the blocking high and picked up large quantities of tropical moisture before moving into California. It appears that this could very likely have occurred in the fall and winter of 1861-1862, when, according to historical accounts and a few early meteorological records, a prolonged siege of precipitation, alternating between cold storms with heavy snowfall and very warm and very heavy rains, pelted the far southwestern United States almost continuously for three months or more, and reaching a climax in middle and late January of 1862--the result of which was the most extensive flooding ever known (before or since) throughout much of California and parts of other States (U. S. Weather Bureau, 1943; Sidler, 1968; Roden, 1966; and others--compare also the 1861-1862 seasonal precipitation indices of Table 2 and Fig. 34).

It appears possible that the heavy precipitation and floods of December 1867 (U. S. Weather Bureau, 1931ff; Sidler, 1968; Ludlum, 1973) might have also resulted from this type of meteorological evolution. Other examples of this type of sequence (on a less intense scale) include the December 1964 floods in northern California and Oregon, the storms and floods of February 1937 in southern California and Arizona, and still less intense cases in February 1901, January 1907, March 1922, December 1932, and January 1974. In these latter cases the warm break-under storms were not of sufficient strength to flush out all of the cold air over the southwestern United States, especially in the interior regions, so that the warm, moist air of these storms merely tended to override the cold air and as a consequence simply added to the existing snow packs. These somewhat weaker events of this type, however, serve to further demonstrate that this type of meteorological sequence can occur at times, along with the potential for severe flooding from warm, heavy rains that fall on top of extensive, ripe snow packs.

Equatorial Ocean Temperatures and Blocking Highs

It is interesting to note that none of the historical cases of heavy precipitation in the southwestern United States cited in the preceding sections--precipitation which resulted directly or indirectly from the effects of large, persistent northeastern Pacific blocking highs--have occurred during the height of any major warm anomalies in the eastern equatorial Pacific Ocean. In fact since January 1899 (the beginning of the published historical weather map series--U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.) there have been no significant blocking highs of <u>any</u> type in the northeast Pacific (with configurations either favorable or unfavorable for precipitation in the southwest United States) between the middle of December and the first of March during major equatorial warm anomalies.

The relatively few cases of major blocking highs in the northeast Pacific that have occurred during Northern Hemisphere winter months in which the equatorial ocean was at all warmer than normal have all taken place either during a temporary dip in the equatorial ocean temperatures or else during the cooling phase following a major warm equatorial anomaly. The high-amplitude patterns of February 1913, December 1951 - March 1952, and the prominent January and February 1969 cases all fall into the former category (equatorial temperature dips), as the probable high-amplitude regime of January 1888 also appears to do, while those of March 1912, January-February 1915, November 1919, December 1923, and January 1949 belong to the latter condition (equatorial cooling)--see Figs. 26-29 and 34. These cases, plus a few fall and spring season examples of blocking highs which have occurred during the warmest parts of major positive equatorial ocean temperature anomalies, will be discussed in the next few sections.

The Unusual Patterns of January 1969

Despite the fact that there was a fairly significant warming of ocean waters in the eastern equatorial Pacific during the period of 1968-1969 (see Figs. 26 and 29; compare also Figs. 23-25), the atmospheric patterns over the north Pacific Ocean during January 1969 were of an extremely high-amplitude, split-flow type (see Figs. 19a, c-f); and it appears likely that these atmospheric configurations were generated and anchored in place to a great extent by highly anomalous sea surface temperature conditions in the subtropical and mid-latitude north Pacific Ocean (see Namias, 1971). It would seem plausible, though, that the strong flow of very moist air which emanated from the deep trough near Hawaii and crossed the west coast of North America in the latitudes of southern California (Figs. 19a, d, f) may have received some impetus from an enhanced Hadley Circulation resulting from the warmer than normal equatorial and near-equatorial water; and it may even be possible that this moist jet stream could have been anchored to the subtropical latitudes (i. e., prevented from proceeding farther northward before striking the coast) in part by the constraints of the equatorially driven Hadley Circulation (as was the case in 1940-1941, 1957-1958, and 1972-1973), as well as by the strong northerly flow and high-latitude trough downstream of the east central Pacific blocking high (see Namias, 1971).

Furthermore, a detailed examination of the Pacific Ocean surface temperatures from the fall of 1968 through January 1969 (Fig. 29; see also Appendix A of Allison et al., 1972; U. S. National Marine Fisheries Service, 1960 et seq.; Namias, 1971) shows that in addition to the moderate positive equatorial temperature anomaly and the subtropical and mid-latitude north Pacific anomaly, there was also a strong warm anomaly in the tropical latitudes north of the equator (roughly 5-15N). This near-equatorial anomaly was of a large enough magnitude during the Northern Hemisphere winter of 1968-1969 to overpower the moderate equatorial anomaly, and as the result, the belt of highest ocean temperatures (in the absolute sense) over the east central part of the Pacific continued to lie significantly north of the equator (around 5-12N) during that period. There was also a very slight dip in the equatorial Ocean temperatures that occurred around December 1968 and January 1969 (as was mentioned earlier); and although these equatorial sea temperatures more than recovered during the Northern Hemisphere spring of 1969, this temporary cooling of the water in the 5N-5S latitude belt acted much like the downward trend following the main peak of a major warm anomaly, and hence served to further strengthen the ocean temperature gradient between the 5-12N belt and the equator.

It seems plausible that this temporary dip in the eastern equatorial Pacific Ocean temperatures may have caused a large portion of the intertropical convective activity to shift to the western Pacific (i. e., the "maritime continent"), where an augmented Hadley Circulation could have contributed, through an accelerated subtropical jet stream and an enhanced Hadley Anticyclone, to the development and maintenance of the deep subtropical lows in the longitudes of Hawaii during January 1969 (see Figs. 19a, d, f; see also Pyke, 1972--Sec. III.C.2.). It also appears likely, as one might expact, that the latitude (5-12N) of the zone of warmest water in the eastern Pacific tended to encourage what remained of the eastern Pacific intertropical convergence zone to seek its more usual position in this part of the globe of approximately 4 to 13N (see, e. g., Figs. 19c-f).

From this latitude the ITCZ convection was more likely able to directly participate in the atmospheric circulation of the eastern north Pacific (which in these longitudes was extremely far to the south of normal--Figs. 19d and f), and, as a consequence, to provide large quantities of sensible and latent heat and moisture, along with a moderate amount of momentum, to the subtropical jet stream--the net result of which was a period of disastrously heavy rainfall in central and southern California during the last two weeks of January 1969.

Equatorial Ocean Temperatures and Other High-Amplitude Patterns

It is also interesting to briefly look at the other high-amplitude atmospheric regimes that have taken place during periods of above normal equatorial ocean temperatures. It can be seen in Figs. 26 and 28 (also to an extent, Figs. 32 and 34) that significant dips in the eastern equatorial Pacific Ocean temperatures took place in 1912-1913 and in 1952--dips of considerably greater magnitude and duration than that of 1968-1969 (the latter of which does not even show up in the 12-month running means of Fig. 26 or Fig. 29). There also appears to have possibly been a brief dip in the equatorial ocean temperatures during the year 1888 (Fig. 34). Perhaps partly as a result of these temporary equatorial coolings, the circulation over the northeastern Pacific assumed high-amplitude configurations during February 1913, in December-January and March of 1951-1952, and possibly also in January 1888, with strong highs in the central and eastern Pacific and deep troughs over or just off the coast of California. The major differences in the configurations among these three seasons and the season of 1968-1969 (intense break-under storms in January 1969, moderate break-under storms in February 1913, no break-under storms in either December 1951 - March 1952 or February 1969, and probably none of major consequence in January 1888) would appear likely, however, to be due primarily to the differences in the sea surface temperature patterns of the north Pacific Ocean.

During the other warmer than normal equatorial ocean cases in which prominent high-amplitude patterns in the eastern Pacific resulted in heavy precipitation over parts of the southwestern United States, such as in March 1912, January-February 1915, November 1919, December 1923, and January 1949, the equatorial Pacific Ocean was quite rapidly cooling down following the peak of a significant warm anomaly (a very prominent warm anomaly in the cases of 1915 and 1919)--see Figs. 26-29. The only possible exceptions to this might be the rainy and snowy period of December 1867 - February 1868 and a brief period of low-snowfall precipitation during mid-February of 1891 (preceding the heavy warm rainfall and flooding of late February)--both of which appear to have occurred during the latter phases of rapid equatorial ocean temperature increases (Fig. 34). The lack of good-quality weather maps and the uncertainties in the smaller details of the Berlage Southern Oscillation Indices (Fig. 34) make it impossible, however, to properly investigate these two winter seasons.

There have also been several fall and spring season examples of high-amplitude atmospheric patterns that have occurred near the maximum of a major equatorial warming, such as those of early March 1958 and early December 1972, plus some occurrences in October, November, April, and May. An explanation of the fall occurrences will be offered in the next section. The spring cases can likely be attributed largely to conditions in the north Pacific which strongly tend to favor the building of large highs in the northeastern portions of that ocean during this season (see, e. g., Pyke, 1972--Secs. III.A.1. through III.A.2.c., and Figs. 10a-14b and 22a-23b). The weakening of the Hadley Circulation and associated subtropical jet stream during the latter portions of the spring is probably also partly responsible for the seasonal increase in the frequency of high-amplitude features over the northeastern Pacific Ocean.

Ocean Temperature Gradients and the Location of the Intertropical Convergence Zone

The atmospheric patterns of January 1969 and the other high-amplitude cases discussed above serve to illustrate a significant refinement to the general rule that a strong northeastern Pacific subtropical jet stream is usually associated with a warm equatorial Pacific Ocean, while high-amplitude patterns, including blocking highs, in the northeastern Pacific are generally associated with cool equatorial ocean conditions. The refinement is that one must consider not only the magnitude of the equatorial anomaly itself but also the equatorial temperatures in relation to those of the non-equatorial tropical latitudes (especially those between approximately 5 and 15N latitude). It is the algebraic sign and the magnitude of the temperature gradient across this region which appears to be perhaps the primary factor in the determination of the mean latitude of the intertropical convergence zone and the associated convective cloud bands.[1] When the temperature gradient is very weak across a fairly wide band of equatorial and near-equatorial latitudes, especially if the temperatures are significantly warmer than normal everywhere (as they usually are under such circumstances), then the intertropical convective activity may be quite intense and cover a fairly broad latitude belt, often centered very near to the equator. If, on the other hand, the temperatures of the ocean north of 5N latitude are several degrees warmer than those along the equator (even if the equator itself is warmer than normal), then

[1] Note that in some cases the intertropical convergence zone (ITCZ) and the equatorial cloud bands may not necessarily be one and the same (Godshall, 1968).

the intertropical activity will likely tend to gravitate toward this slightly higher-latitude belt (and will occasionally appear in the tropical belt south of the equator as well--see, e. g., Kornfield et al., 1967; Bjerknes, 1969a).

This tendency for a non-equatorial centering of the mean intertropical convergence zone, even during years of somewhat warmer than normal eastern equatorial Pacific Ocean temperatures, appears to result from several possible situations or conditions:

First, if the magnitude of the equatorial warm anomaly is anything less than quite large, the temperatures of the 5-15N latitude belt (which are normally the warmest of all latitude belts, and which, according to the correlations of Allison et al., 1972, are also likely to be somewhat above normal during an equatorial warm anomaly) will likely continue to be warmer than those along the equator.

Secondly, if the magnitude of the temperature anomaly north of 5N latitude is quite exceptional (as in 1968-1969), then even a strong positive anomaly along the equator might not be able to overcome the temperature gradient that has been augmented by this non-equatorial anomaly.

Thirdly, because of the typical lag in the peaks of the non-equatorial warm anomalies (compared to those along the equator), and because of the more rapid cooling of the equatorial ocean that frequently takes place because of upwelling (see Fig. 29 and earlier discussions), a significant temperature gradient between 5-15N and the equatorial belt can often become re-established very shortly after the peak of a major equatorial warm anomaly (as appears likely to have taken place in March 1912, January-February 1915, November 1919, December 1923, and January 1949).

Fourth is the fact that during the Northern Hemisphere fall season (roughly October to mid-December), the northern tropical belt is still in the process of cooling down, while the equatorial zone is usually still warming up from the normal early spring (late August - October) trade wind maximum of the Southern Hemisphere and its associated equatorial upwelling. This maintains at least a slight temperature gradient between around 5-15N and zero degrees latitude during these months, even in years of very large equatorial warm anomalies, as can be seen in Figs. 37 and 38: the charts of maximum ocean surface temperatures for November and December respectively (reproduced from Laviolette and Seim, 1969).

This gradient and its probable consequences (a weaker intertropical convergence zone displaced significantly north of the equator) can perhaps partially explain the occurrence of a large and fairly persistent high-amplitude ridge in the northeastern Pacific during December 1972 (reflected in part in Fig. 13a) and on a number of occasions during October and November, including that of October 1972 (Fig. 11a) and the more minor ridges of October and November 1957 (Figs. 3a and 4a). It would appear, though, that the primary causes of these large eastern Pacific ridges in late 1972 and in other fall seasons are likely to lie in the temperature configurations of the north Pacific Ocean (Namias, 1974, and other articles).

SUMMARY OF GENERAL RELATIONSHIPS

From the material of the previous section, along with that discussed earlier, it now appears possible to formulate a set of general guidelines concerning the relationships between equatorial ocean surface temperatures and the atmospheric circulation and precipitation patterns affecting the southwestern United States during the Northern Hemisphere winter and early spring months:

During periods in which the surface temperatures of the eastern equatorial Pacific Ocean are significantly above normal, and in which these equatorial waters are warmer than, or at least as warm as, those of any other latitude belt over these bands of longitudes, it is likely that the atmospheric circulation patterns over the northeastern Pacific Ocean and western North America will be of the strong and persistent subtropical jet stream type--a type of pattern in which Pacific cyclones of moderate temperature and moisture content move inland from the ocean at low latitudes and march across the southwestern United States from west to east at frequent intervals, dropping moderate to heavy precipitation over large areas on an almost continually recurring basis. This type of storm pattern will often tend to fill reservoirs and significantly add to snow packs in the higher mountains, thus setting up the potential for some late-season flooding on certain of the large river systems. Intense convective cells imbedded within the general storms of this type of pattern may possibly on occasion also cause brief, local flooding on a few of the smaller watersheds. Because of the speed of movement and the moderate moisture content of these Pacific cyclones, however, there should not too often be much widespread flooding over intermediate-sized river basins (roughly 1000-20,000 square kilometers) from the individual storms of this type.

On the other hand, during periods of near normal, or especially below normal, eastern equatorial Pacific Ocean temperatures, or during periods of rapidly cooling equatorial waters--any period in which the eastern equatorial Pacific Ocean is significantly cooler than the ocean belt between approximately 5 and 15N latitude--one can expect a much greater likelihood that high-amplitude atmospheric circulation patterns, often with large blocking highs and deep troughs or cut-off lows, will form and tend to persist. The weather patterns over the southwestern United States during such periods of cool or cooling equatorial oceans--patterns which can range from very dry, to cold and wet, to very warm and very wet (with the potential of severe flooding on all sizes of basins)--will depend to the greatest extent upon the exact locations, intensities, and configurations of these various high-amplitude features. These in turn may be determined in part by magnitudes and configurations of equatorial and near-equatorial ocean temperature patterns, but it appears more likely that they would be determined for the most part by sea surface temperature patterns in the subtropical and mid-latitude north Pacific Ocean (see Namias articles).

APPLICATIONS TO THE SEASONS OF 1861-1862 AND 1889-1890

A knowledge of the relationships discussed thus far in this paper can now be applied to two unusually wet seasons which occurred in California and parts of other southwestern States during the latter half of the 19th Century. Unfortunately no daily weather maps appear to be available for the winter of 1861-1862, and only very crude maps (e. g., U. S. Signal Service, 1870-1891) for 1889-1890. Precipitation data from those years are also scanty. There are, however, a number of clues which can be gleaned from these Signal Service maps and from Monthly Weather Review, from Fig. 34, from several U. S. Weather Bureau publications, and from various historical accounts and other sources. Although it occurred earlier, the 1861-1862 atmospheric circulation and equatorial ocean temperature patterns are for various reasons somewhat easier to reconstruct than those of 1889-1890, as will be discussed.

The Catastrophic Flood Season of 1861-1862

Throughout a large portion of California and other parts of the southwestern United States the floods of the 1861-1862 winter season were by far the greatest ever known before or since that time. Because of the severity of these events, a number of historical accounts have been written and hydrometeorological studies conducted of the events of that winter.

According to the U. S. Weather Bureau (1943) precipitation in the area of the Sacramento River basin of California began as early as 9 November 1861 and persisted intermittently with only occasional significant letups through at least late January of 1862. Most precipitation amounts during November 1861 averaged about normal to somewhat above normal. This was followed by about two to three times the normal precipitation in December and up to five times the normal amounts in January 1862. Above normal precipitation also fell during February of that season. The totals for the two calendar months December 1861 - January 1862 (U. S. Weather Bureau, 1931ff) include 23.68 inches (128% of long-term mean annual precipitation) at Sacramento, 33.90 inches (153% of mean annual) at San Francisco, and 45.35 inches (129% of mean annual) at Shingle Springs (elevation 1415 feet) in the Sierra Nevada foothills near Placerville. About two-thirds of these December-January totals generally fell within an 18-day period during mid-January. Considerably greater amounts than those listed here are likely to have fallen in the higher Sierras northeast of Sacramento, where mean annual precipitation in some places exceeds twice that of Shingle Springs.

At times during this extremely stormy period heavy snow fell over all of northern California and down to low elevations in central and southern California, while an exceptionally cold arctic air mass, with record-breaking low temperatures, prevailed over the Pacific Northwest United States. On several occasions during December 1861 and January 1862 these conditions rapidly gave way to very warm and very heavy general rains, as the cold air was replaced by the influx of unusually warm, moist air from out of the southwest. These heavy rains combined with the rapid melting of large quantities of snow to produce generally the worst flooding on record throughout most of California (U. S. Weather Bureau, 1943; McGlashan and Briggs, 1937; Hoyt and Langbein, 1955; Roden, 1966; Sidler, 1968; LaFuze, 1971; Lynch, 1931; and others).

The first of these major episodes of warm, heavy rain occurred over the northern portions of California on 7 December 1861. In Sacramento the weather observer described the rain as "almost tropical," according to the U. S. Weather Bureau (1943). Another heavy rainfall period occurred in this region beginning on 22 December and culminated in severe flooding on 28 December. In southern California, meanwhile, "a gentle rain," or "a nice, pleasant rain" began on Christmas Eve and continued through the Holidays (LaFuze, 1971; Sidler, 1968).

After the first of January the rains became generally harder and colder throughout the State, and heavy snows began piling up in all mountain areas. On 5 and 6 January "severe snow showers" occurred in the foothills of the Sacramento Valley, and snow depths ranged from 6 to 12 inches over the valley floor only 12 to 30 miles northwest of Sacramento, according to the U. S. Weather Bureau (1943). From 8 to 11 January warm, heavy rains hit all of California, melting much of the snow and producing disastrous flooding, particularly in the State's Central Valley, where the Sacramento Delta region is described as having become one vast lake, 20 miles wide and 250 miles long (U. S. Weather Bureau, 1943; Roden, 1966; and others).

During the ensuing days colder air once again settled into the far western United States, and between 15 and 18 January a severe arctic outbreak spread over the region, causing extremely low temperatures over the Pacific Northwest--with 16°F (-9°C) recorded even as far south and west as Fort Umpqua, near the coast of south central Oregon (Roden, 1966). In the intensifying baroclinic zone south of this extremely cold air, rainfall over southern California and snowfall over northern California increased. Then, beginning on 18 January another invasion of very warm and very moist air from the southwest spread over the entire Far West, with temperatures up to 59°F (15°C) recorded along the Oregon coast. Very heavy downpours resulted throughout California, again melting great quantities of snow, and resulting in unparalleled flooding throughout large portions of the State. In the Sacramento Valley the severe flooding of 9-11 January was repeated, and this time conditions extended over the northern portions of the basin as well. In southern California extremely heavy flooding was reported on a number of streams, including the greatest flood of record--by approximately a factor of three--on the Santa Ana River near San Bernardino on 22 January 1862 (Sidler, 1968), plus severe flooding downstream on this river in the Anaheim area (Hoyt and Langbein, 1955).

Toward the end of the month another extreme cold wave spread over the far western States, and more heavy snow was reported. In Sacramento three inches of snow was recorded in 18 hours on 29 January (U. S. Weather Bureau, 1943), and accounts of snow 16 feet deep in the San Bernardino Mountains of southern California on 6 February 1862 are cited by LaFuze (1971).

In Arizona a similar, but perhaps slightly less severe, precipitation and flood pattern is believed to have prevailed. Portions of the Gila River system are reported to have experienced flood crests second only to those of early 1891, and the peak 1862 flow at one location on the lower Colorado River is estimated to have perhaps exceeded all others, including that of 1891 and possibly that of 1884 (Smith and Heckler, 1955).

Although no weather maps or other meteorological analyses are directly available for this region during this period of time, some verbal sketches of the conditions across the far western United States have been put together by the U. S. Weather Bureau (1943) and by Roden (1966). These indicate for the heavier storms the likelihood of a strong frontal zone initially stretched across central or southern California and out into the Pacific to the southwest, with extremely cold air over the Pacific Northwest and with cold, northerly winds blowing down the Sacramento Valley. As each major cyclone disturbance developed along this front and approached northern California and Oregon from the southwest, an overrunning and a great northeastward displacement of the cold air resulted in very heavy precipitation and rapid snow melt, according to the U. S. Weather Bureau (1943).

The sequence of meteorological conditions listed here, along with the precipitation events, suggest the greatest likelihood of a very high-amplitude, split atmospheric flow pattern--one in which the cold air from the north and the very warm, very moist air from the southwest were colliding almost directly over California. The extremely low temperatures in the Pacific Northwest and the occurrence of heavy snow over the low foothills and at times over the Sacramento Valley floor indicates the necessity of a high-amplitude configuration, with a very deep upper level trough or low over northern and central California. The sudden transition to very warm and very heavy rainfall over the entire region likely precludes a simple retrogression of this trough to an offshore position and the rather gradual infiltration of warm, moist air that would take place. More than likely a break-under type of storm from the subtropics was involved during each sudden warming and onset of heavy rain.

Further evidence of this type of synoptic pattern can be gathered from an examination of some of the rather few available mean temperature and precipitation records for December 1861 and January 1862 over other parts of the country (U. S. Weather Bureau, 1931 ff; Ludlum, 1968a). These sources tend to indicate for those two months significantly higher than normal temperatures over Tennessee and adjacent States, considerably lower than normal temperatures in Minnesota, around double the normal precipitation for those months across the central Great Plains and Mississippi River Valley, and near normal conditions along the central and north central Atlantic coast. This would tend to imply a broad low-latitude mean ridge over the south central United States, a cold upper trough and surface high over the northern Great Plains, a fast west-southwesterly jet stream and frontal zone across the central Great Plains, and a generally west-northwesterly flow over the middle Eastern Seaboard.

These downstream patterns would fit in well with a high-amplitude blocking high in the extreme eastern Pacific with a split flow: one branch of the jet stream shooting southward down the west coast of Canada and the United States, perhaps cutting back somewhat around a deep trough over northern and central California, and the other branch cutting under the blocking high and approaching central and southern California from tropical latitudes to the southwest, with the zone of convergence of these two branches of the jet stream likely shifting around by several degrees of latitude and longitude in conjunction with individual synoptic-scale disturbances--thus producing the alternating conditions between heavy snow and very heavy, warm rain in California.

As for the equatorial ocean temperatures during this period, one should expect from the relationships discussed in preceding sections of this paper that the eastern equatorial Pacific Ocean in 1861-1862 would have been significantly cooler than normal or at least cooling down quite rapidly following a significant warm anomaly. Fig. 34 suggests the former. The Southern Oscillation Indices of Berlage were negative from 1859 to 1864--thus implying a fairly prolonged period of below normal eastern Pacific equatorial temperatures during these years.

It is also extremely interesting to note that the summer of 1861 was a season of an exceptionally heavy Southwest Monsoon in India. During this particular year all of the world's record rainfall amounts for every duration from one month (366.14 inches) to one year (1041.78 inches) and two years (1605.05 inches) were set at the highly orographically favored station of Cherrapunji, India (U. S. Weather Bureau, 1960; and others)--the latter values covering a period which had begun in 1860. This would also tend to indicate a great likelihood of significantly below normal temperatures in the eastern equatorial Pacific Ocean, as can be seen from the following relationships:

It has been shown by Bjerknes, Walker, and others that during periods in which the eastern equatorial Pacific Ocean is relatively cool, and the sea level pressure over the Indonesian region is generally low, the Walker Circulation will generally be quite strong--not only the branch of the circulation from the South American west coast to Indonesia, but also a branch of this tropical zonal circulation feeding into the Indonesian maritime continent from the west. During the Northern Hemisphere summer, this westerly branch over the Indian Ocean migrates and expands somewhat northward, and thus reinforces the Southwest Asian Monsoon.

Summer rainfall in India has been strongly correlated by Walker to the magnitude of the Southern Oscillation, and in fact this element is used by Dr. Walker as one of his components in the computational formula for the June-August Southern Oscillation Index. (A correlation coefficient of +0.76 has been computed by Walker and Bliss, 1932, between the component India rainfall and the complete June-August Southern Oscillation Index over the period 1875-1929.) Thus a year having a strong Southwest Monsoon over India is likely to be one of a positive Southern Oscillation Index (as computed by Walker) and a cooler than normal eastern equatorial Pacific Ocean (such as the year 1917), while a weaker Indian Monsoon in summer would likely be associated with a negative (Walker) Southern Oscillation Index and an eastern equatorial Pacific warm anomaly (such as in 1877)--compare Fig. 33.

Therefore, from the above discussions, one can be virtually certain that the unusual flood-producing conditions in California and other southwest States during the winter of 1861-1862 were associated with a very high-amplitude, blocking high type of atmospheric circulation pattern in the northeastern Pacific Ocean, and that this pattern was most likely one having a split flow, with the two branches converging over or very near central California. One can also be quite certain that this extreme pattern occurred during, and was very possibly generated and maintained in part by, a considerably cooler than normal eastern equatorial Pacific Ocean and the various meteorological features resulting from this oceanic anomaly: a weakening and northward displacement of the intertropical con-convergence zone in the eastern Pacific, an intensification of convective activity over the maritime continent, an intensification of both the subtropical jet stream and the Hadley Anticyclone above the western Pacific, and the probable development of an intense Kona low or trough not far from Hawaii--a trough which served to maintain the northeastern Pacific blocking high, and a trough which on occasion opened up to the northeast and pumped extreme quantities of tropical moisture into California. Anomalous sea surface temperature patterns in the north Pacific Ocean also, of course, likely played a major role in the development and sustentation of the highly unusual atmospheric features which led to these unprecedented California rains and floods.

The Complicated Patterns of 1889-1890

Ironically it is somewhat more difficult to reconstruct the equatorial ocean temperature and atmospheric circulation patterns for the 1889-1890 season than it is for that of 1861-1862. This is largely because of more complicated and more rapidly changing conditions between 1888 and 1891 than during the early 1860's and because of the fact that more accounts have been written and more investigations conducted concerning the great floods of 1861-1862 than have been done with regard to the latter season.

The 1889-1890 rainy season in the far southwestern United States began early. Significant rain fell in late August and early October of 1889, but these were likely of tropical origin and will be treated in this paper's sections on summer precipitation (including Tables 3 and 4). During the remainder of October 1889--a month in which precipitation exceeded 12 times normal at some California stations--the atmospheric patterns were presumably quite like those of October 1957 (Fig. 3a) and October 1972 (Fig. 11a), with a fairly high-amplitude trough near the California coast and a mean ridge offshore.

November precipitation during that year was mostly near normal, but the December totals were the greatest that have ever been recorded for any month of any year at a number of southern California stations, with very large amounts of precipitation also reported that month in northern California and in the general Four Corners area of the interior southwestern United States.

The rainfall of December 1889 was distributed fairly evenly throughout the month over most of California, with 20 days of measurable precipitation in Los Angeles and comparable numbers of days elsewhere (McAdie, 1903; U. S. Corps of Engineers, 1940ff; and others). Except for 12-13 December, when more than four inches fell in Los Angeles and 5 to 7 inches (and perhaps more) fell in the sparsely gaged mountain areas, most of the precipitation during that month was of the recurring moderate-intensity type, with generally moderate temperatures (and hence no extreme flooding was reported). This pattern might offhand tend to suggest the strong subtropical jet stream type of atmospheric configuration, with a long series of rapidly moving cyclones. It turns out, however, that this was probably not the case in December 1889.

The sketchy individual weather maps of U. S. Signal Service (1870-1891) for December 1889, plus the mean sea level pressure chart for that month (MWR; McAdie, 1903) shows the predominance of low pressure along and off the Pacific Northwest coast, occasionally moving southward to off the southern California coast, with generally easterly to southeasterly surface winds over California, and a very flat pressure field over the entire interior western United States (as contrasted with a normally moderate high pressure belt across California and the Great Basin--U. S. Weather Bureau, 1952; O'Connor, 1961; see also Pyke, 1972--Figs. 10e and 11c). Furthermore, conditions over the eastern portions of the United States very strongly suggest the presence of a very large, warm, dry ridge or closed high aloft centered over the south central United States during December 1889: Some parts of this region, especially eastern Texas, recorded zero rainfall (not even a trace) during the entire month, and at a number of stations in the lower Mississippi Valley December 1889 was the warmest December in all history--by almost 9 degrees Fahrenheit (5 degrees Celsius) above the second warmest December--and around 18°F (10°C) above normal (U. S. Weather Bureau, 1931 ff; Ludlum, 1970-1972).

These factors, combined with near normal temperatures over the southwestern United States and somewhat cooler than normal temperatures over the Pacific Northwest (U. S. Weather Bureau, 1931 ff), would tend to suggest the presence of a deep mean trough, surface and aloft, along and just off the west coast during December 1889, and a high-amplitude ridge or blocking high to its northwest, possibly with one or more weak to moderate break-under type storms during the month.

By January 1890 the pattern had evolved into a cold storm type, as precipitation amounts dropped to about one-third to two-thirds of the December 1889 values, but with extremely heavy snowfall in the Sierra Nevada Mountains of California (Ludlum, 1973), and as the monthly mean temperatures dropped from near normal everywhere in December to several degrees below normal over the southern and central coastal regions and 15 to 20 degrees Fahrenheit (8-11 degrees Celsius) below normal over the northern Rockies (U. S. Weather Bureau, 1931 ff). This would suggest a coherent atmospheric flow pattern with a strong ridge offshore and a deep trough along the coast or just inland--perhaps somewhat similar to that of January 1916.

The months of February and March of 1890 appear to have continued the general pattern of January, but with a progressive deamplification and weakening of all anomalous conditions, and a gradual return toward normal.

As for the equatorial ocean temperatures during this season, Figs. 31-34 show that between the prominent peaks (troughs) in the Berlage (Walker) Southern Oscillation Indices of 1888-1889 and 1891 there was a very marked reversal of the Southern Oscillation, with the lowest Berlage values and the second highest Walker values (topped only by those of

1916-1918) of their respective periods of calculation. This major reversal of the Southern Oscillation, which was centered during the Southern Hemisphere summer and Northern Hemisphere winter of 1889-1890, should correspond to a very rapid and very extensive equatorial cooling, and thus one should expect that the atmospheric circulation patterns over the Northern Hemisphere Pacific would indeed likely be of a high-amplitude type instead of characterized by a strong quasi-zonal subtropical jet stream. These high-amplitude atmospheric patterns and the various changes which took place in them from October 1889 through March 1890 were very probably also guided and perhaps forced to a great extent by significant and changing anomalies in the north Pacific Ocean surface temperatures.

SUMMER STORMS AND OCEAN TEMPERATURES

In addition to the general cool-season precipitation regime, the interior portions of the southwestern United States also experience a distinct summer rainfall season (the primary rainy season of the year in some areas). This summer precipitation falls primarily from convective air mass thunderstorms, although on occasion some generalized precipitation may fall over certain regions from a synoptic-scale disturbance, such as an easterly wave, a dissipating tropical storm, an unusually low-latitude penetration (for that time of the year) of an extratropical cyclone system, or a combination of such disturbances. Even this generalized precipitation, however, usually tends to be of a convective nature throughout the summer months and into the early fall (until around mid-October).

In nearly all cases it appears that the ocean surface temperatures in the Sea of Cortez (Gulf of California) and in the open Pacific Ocean off the coasts of California, Baja California, and mainland Mexico are likely to play a significant role in the supply of the moisture content and instability of the air masses necessary for this convective activity over the southwestern United States: the higher the ocean temperature, the greater the moisture supply and the more unstable the air. Warm oceans are also vital to the generation and maintenance of tropical cyclones. Therefore one should expect that during summers of warmer than normal temperatures off the west coast of California and Mexico, there would be heavier than normal precipitation in general over much of the southwestern United States, and the chances of flooding in various areas would be significantly greater--both local flash flooding in very small drainage basins (less than around 1000 square kilometers) from air mass thunderstorms, and general flooding in intermediate-sized basins (approximately 1000-20,000 square kilometers) from synoptic-scale disturbances.

Of course, some of the moisture for the precipitation in the southwestern United States--especially for areas east of the Continental Divide--comes from the Gulf of Mexico. It has been demonstrated, however, by Hales (1972, 1973, 1974), Hansen (1975a, 1975b), Brenner (1973, 1974), and others (see discussion by Pyke, 1972--Sec. IV.B.1.) that the primary source for low-level moisture (a very necessary component of the total air column moisture, and a very necessary ingredient for instability) over the more western portions of the Southwest must be the Sea of Cortez and the open Pacific Ocean, especially the warmer ocean regions southeast and southwest of Baja California. Therefore, especially for the <u>far</u> southwestern portions of the United States (areas such as Arizona, southern Nevada, and southern California), the total precipitation of a summer and early fall season, as well as the potential for local and intermediate-sized basin floods during these months, is likely to be quite highly dependent upon the surface temperatures of the Pacific Ocean off the west coast of Mexico, including the Sea of Cortez.

Relationship to Equatorial Ocean Temperatures

During the Northern Hemisphere summer season the influence of ocean temperatures in the equatorial Pacific upon mid-latitude precipitation patterns should be negligible, since summer (in each hemisphere respectively) is the season of the weakest Hadley Circulation and hence the weakest connection between equatorial latitudes and middle latitudes, except for the large cross-equatorial circulation regime in the longitudes of the Asian Monsoon.

The interannual variations in convective precipitation potential in the southwestern United States cannot be considered entirely divorced from eastern equatorial Pacific Ocean temperatures and El Niño phenomena, however. It has been demonstrated by Allison et al. (1972) and others that the sea surface temperatures along the west coast of the United States and off the west coast of Mexico and Central America are generally quite highly correlated with those of the eastern equatorial Pacific, as can be seen very readily in Figs. 29 and 30 (reproduced from Allison et al., 1972). Table 9 of Allison et al. (1972) shows that the correlation coefficients between sea surface temperature anomalies along the west coast of the United States and those of the eastern Pacific in the various latitude belts from

20-30N to 0-10S range from +0.61 for 0-10S to +0.87 for 10-20N, with lag times ranging from +4 to -8 months. Thus during periods of above normal equatorial ocean surface temperatures, the ocean temperatures off of western North and Central America should also <u>tend</u> to be higher than normal.

This relationship is not mere coincidence. A number of authors (including Bjerknes, 1961, 1966b, 1974b; Wyrtki, 1973; Namias, 1973c; Krueger and Winston, 1975; Allison et al., 1972; and other articles by these and other authors) have related equatorial Pacific Ocean warmings to weakenings in the trade wind circulation of not only the Southern Hemisphere (the circulation which is primarily and directly responsible for the cooling by upwelling--or lack of it--along the equator) but also the Northern Hemisphere. Such weakening of the Northern Hemisphere trades would tend to weaken the cold water advection and upwelling off the California and Baja California coast, allowing these waters to warm. This would also result in some decrease of the marine layer cloudiness (stratus and strato-cumulus) in these regions, allowing more penetration of solar radiation and hence further warming.

Wyrtki (1973), Namias (1973c), Bjerknes (1961, 1966a, 1966b, 1974b), and others have also discussed the role which the Equatorial Countercurrents (both North and South) play in the relationships between the trade winds and the equatorial Pacific Ocean temperatures: When the trade winds of either hemisphere are strong, the easterly wind stress weakens the west-to-east countercurrent of that hemisphere (the Northern Hemisphere Countercurrent is normally located between approximately 4N and 10N latitude--see Wyrtki, 1973; Namias, 1973c). When the trade winds weaken, the countercurrent flows more strongly from the western Pacific, advecting warmer water into the eastern Pacific region. This larger than normal reservoir of warm water on either side of the equator is then able to advect into the equatorial zone--once the strong Ekman divergence along the equator generated by the easterly winds of the Southern Hemisphere trades has greatly weakened--and thus provide for warmer than normal equatorial waters.

In addition to the warm water supplied by the North Equatorial Countercurrent and the reduction of cooling by the upwelling effects of the northeast Pacific Ocean trades, there also appears to be a very interesting, self-perpetuating factor which would tend to sustain higher than normal ocean temperatures off the west coast of Mexico, particularly west of Baja California. It is noted by Roden (1971, 1972) (also discussed by Pyke, 1972--Secs. III.B.3., IV.B.1., and IV.B.2.) that the region near Cabo San Lucas (the southern tip of Baja California) normally represents a strong, complex oceanic frontal zone--a zone of convergence of three currents bearing water of widely different temperatures and significantly different salinities. The primary contrast in this area is between the cold, upwelled water of the California Current from the northwest and the warm, lower-salinity water of the North Equatorial Current from the southeast. The water associated with this latter current, being of lower density (because of both its higher temperature and lower salinity), tends to spread out northwestward over the colder California Current water and at times can result in an almost discontinuous jump in the surface water temperatures off the southern, and occasionally the northern, Baja California west coast. This warm water normally assists in the moisture supply and instability for the production of air mass summer thunderstorms over the mainland of Mexico and to a lesser extent the peninsula of Baja California. Runoff from these thunderstorms, according to Roden (1971, 1972), enters the ocean and slightly dilutes the sea water, thereby lowering its salinity and its density. It would seem that during periods of weaker than normal Northern (and Southern) Hemisphere trade winds and a stronger than normal North Equatorial Countercurrent, the warm water supply of the (westward- and northwestward-drifting) North Equatorial Current would be augmented. This would serve to further enhance the convective precipitation over Mexico, and the resulting runoff would further lower the salinity of this North Equatorial Current water (and perhaps also raise its temperature because of the trajectory of such runoff over greatly heated terrain). Thus, during such periods of weakened Pacific trade winds one might expect a stronger North Equatorial Current of slightly warmer and less dense water, as well as a weaker and less cool California Current--the result of which could likely be a very significant northward shift of the zone of convergence (at the surface) between these two currents and a major warming of the water off the west coast of Baja California, and in extreme cases (such as in September 1939) off of southern and central California as well. Such a warming of the ocean in this region is bound to have a positive effect upon the summer and early fall precipitation over the southwestern United States, both directly, in terms of air mass convection, and indirectly, in terms of tropical cyclones and other disturbances.

Furthermore, it appears that during periods of weaker trade winds and equatorial ocean warmings, the entire atmospheric circulation over approximately the 20-40N latitude belt across the eastern Pacific and North America tends to become a bit more tropical in nature (i. e., appears to go into a more tropical mode), especially during the summer and early fall months, with an increase in the number of synoptic-scale tropical disturbances, from easterly waves to full-blown hurricanes. If this is indeed true, then one would expect yet another factor to operate in favor of greater summer and early fall precipitation over the southwestern United States during such periods of weakened trades and a warmer than normal subtropical, tropical, and equatorial eastern Pacific Ocean.

The historical records tend to bear this out. A comparison of June through September precipitation at a number of Arizona, southern Nevada, and southeastern California stations (U. S. Weather Bureau, 1931ff, 1953ff, 1964-1965; U. S. Weather Bureau, ESSA, and NOAA, 1897 et seq., 1951 et seq.) with the records of equatorial and higher-latitude eastern Pacific Ocean temperatures (Figs. 29-30, and by extension, Figs. 23-28 and 31-34, plus Table 1) shows that many, although by no means all, of the wetter summers have tended to occur during, or have been clustered around, periods of warmer than normal oceans. The same relationship also holds generally true for the month of October--a month whose precipitation in the southwestern United States frequently consists of a mixture of tropical type disturbances and early-season extratropical cyclones and frontal systems with convective instability enhanced by the yet-warm oceans off the coast.

Rare-Event Storms

An even better reflection of above normal ocean temperatures than total warm-season precipitation is the incidence of some of the more rare storm events in the southwestern United States, such as tropical cyclones and extreme local rainfall amounts.

(1) Extreme local precipitation. It is noteworthy that a large number of the heaviest single-station rainfall intensities on record in this part of the country--most of them summer or early fall thunderstorm events--have occurred during, or within several months of, a significant equatorial warm anomaly, as can be seen in Table 3. This appears to be especially the case for the truly extreme local precipitation events, such as that of Campo, California, 12 August 1891.

Table 3: Some Extreme Single-Station Rainfall Amounts in the Southwestern United States, 1878-1975

Date	Location	Rainfall/Duration[a]	Data Sources[b]	[c]	Equatorial Warming[d]
11 Jul 1878	Tucson, AZ	5.10 in / 1? hr[e]	H, M, O		1877-1878 EN
12-13 Oct 1889	Encinitas, CA[f]	7.58 in / 8 hrs	F, G, L, M, O, R	g	1888-1889
7 Aug 1890	Palmetto, NV	8.6 in / 1.5 hrs[h]	D	g	1890-1891 EN
11 Aug 1890	Palmetto, NV	8.8 in / 1 hr[h]	D, E, G, H	g	1890-1891 EN
12 Aug 1891	Campo, CA	11.5 in / 80 min	D, E, F, G, H, J, L, M, P, S, T		1890-1891 EN
28 Aug 1898	Fort Mohave, AZ	8 in / 45 min	A, D, E, G, H	i	1899-1900 EN?[i]
1 Aug 1906	Casa Grande Ruins, AZ	5.4 in / 6.5 hrs	I, P		1904-1906[j]
2 Jul 1910	Carnegie Desert Lab, AZ	5.0 in / 2 hrs	I	i	1911-1912 EN?[i]
5 Oct 1911	Gladstone, CO[f]	8.05 in / 1 day[k]	A, D, P		1911-1912 EN?
25 Jan 1914	Santa Barbara, CA[ℓ]	4.50 in / 4 hrs[m]	U		1913-1915
9 May 1915	Kennett, CA[ℓ]	8.25 in / 8 hrs	A, F, G, M, O		1913-1915
12 Sep 1918	Wrights, CA[f]	3.5 in / 1 hr?[k,n]	F, G	++	1917-1919 EN?
14 Sep 1918	Red Bluff, CA[f]	4.70 in / 3 hrs	C, F, G	++	1917-1919 EN?
1-2 Oct 1918	Redding, CA[f]	5+ in / 6? hrs[o]	A	++	1917-1919 EN?
18 Jul 1922	Campo, CA	7.10 in / 2 hrs	A, D, G, H, J, L, O	-	1923 EN?
18 Jul 1922	Squirrel Inn, CA	5.01 in / 90 min	A, H, J, L, P	-	1923 EN?
5 Apr 1926	Opid's Camp, CA[ℓ,p]	3.83 in / 2 hrs[q]	K	++	1925-1926 EN
30 Sep 1932	Tehachapi, CA[f]	4.38 in / 6.5 hrs[r]	F, G, O, P, V, W	-	1929-1932 EN?[j,s]
2 Mar 1938	Opid's Camp, CA[ℓ,p]	10.86 in / 8 hrs[t]	P	o	none[u]
5 Aug 1939	Sierra Ancha, AZ	5.02 in / 140 min	H, I, P, Q	+++	1939-1942 EN
24 Sep 1939	Indio, CA	6.45 in / 6 hrs[v]	F, G, L, P, X	+++	1939-1942 EN

(table continued on next page)

Table 3 (cont.)

Date	Location	Rainfall/Duration[a]	Data Sources[b]	[c]	Equatorial Warming[d]
21 Oct 1941	Avalon, CA[ℓ]	5.53 in / 3.5 hrs	F, G, L	++	1939-1942 EN
22 Jan 1943	Hoegee's Camp, CA[ℓ,p]	13.36 in / 12 hrs[w]	J, L, P	o	1943-1944 VM
3-4 Mar 1943	Sierra Madre, CA[ℓ]	3.32 in / 3 hrs[x]	G, P	o	1943-1944 VM
29 Sep 1946	Cucamonga, CA[f]	3.5 in / 1 hr[y]	P, Y	o	1945-1946 M
30 Sep 1946	Julian, CA[f]	3.78 in / 1 day[k]	A	o	1945-1946 M
19 Aug 1954	Queen Creek, AZ	5.3 in / 8-9 hrs[z]	P	o	none[u]
18 Jul 1955	Vallecito, CA	7.1 in / 70 min	E, G, H, L, P	--	none[u]
19 Jul 1955	Chiatovich Flat, CA	8.0+ in / 2.5? hrs[α]	D, E, F, G, H, J, L, Z	--	none[u]
4 Aug 1955	near Needles, CA	5.25? in / unknown[h,β]	P	--	none[u]
23 Aug 1955	Gila Mountains, AZ	6 - 10? in / 2-3? hrs[h,γ]	P	--	none[u]
29 Jul 1958	Camp Angelus, CA[f]	2.45 in / 75 min[δ]	A′	+++	1957-1958 EN
16 Aug 1958	Morgan, UT	6.75 in / 1 hr[ε]	E, G, H, P	+++	1957-1958 EN
6 Sep 1958	Jackson Lake, CA	4.38 in / 1 day[k]	P	+++	1957-1958 EN
18 Sep 1959	Newton, CA[ℓ]	10.6 in / 5 hrs?[ζ]	F, G	++	1957-1958 EN[η]
16 Aug 1963	Glendale, AZ	5.21 in / 3.75 hrs	P	+	1963-1964 M
13 Nov 1965	San Marcos Pass, CA[ℓ,p]	4.58 in / 3 hrs[θ]	P	++	1965-1966 EN.
9 Apr 1966	Redding, CA[ℓ]	3.48 in / 3 hrs[ι]	B, J	o	1965-1966 EN
8 Mar 1968	Bonita, CA[ℓ]	3.15 in / 3 hrs	B′	+	none[u]
25 Jan 1969	Juncal Dam, CA[ℓ,p]	10.72? in / 8 hrs[κ]	C′	+	1968-1970 M
5 Sep 1970	Workman Creek, AZ[f,ℓ,p,λ]	8.13 in / 12 hrs[μ]	B, P	o	1968-1970 M[j]
5 Sep 1970	Bug Point, UT[f,ℓ,λ]	6.0 in / 11 hrs[ν]	A, P, D′	o	1968-1970 M[j]
7 Jun 1972	Bakersfield, CA	3.50 in / 70 min	L, E′	o	1972-1973 EN

(table continued on next page)

Table 3 (cont.)

Date	Location	Rainfall/Duration[a]	Data Sources[b]	[c]	Equatorial Warming[d]
22 Jun 1972	Phoenix, AZ	5.25 in / 2? hrs[ξ]	H, P	o	1972-1973 EN
6 Oct 1972	Sunflower, AZ[f]	5.38 in / unknown[k,o]	N	++	1972-1973 EN
18 Jan 1973	San Luis Obispo, CA[ℓ]	4.1 in / 3 hrs[π]	P	+	1972-1973 EN
18 Jan 1973	San Marcos Pass, CA[ℓ,p]	4.8 in / 4 hrs[ρ]	B	+	1972-1973 EN
4 Dec 1974	San Marcos Pass, CA[ℓ,p]	6.4 in / 6 hrs[σ]	B	--	none[u]

[a] Outstanding single-station rainfall amounts (in inches--measured or estimated) for selected durations in the southwestern United States (not necessarily total storm amounts), which fit the following criteria:

(1) Duration of 12 hours or less (except in a few outstanding cases where durations of less than one observational day were not measured, but where the available evidence (flooding, etc.) indicated that most if not all of the precipitation fell within a short period of time).

(2) Amount greater than 3 inches in areas over and west of California's coastal and Sierra Nevada mountain ranges, or greater than 5 inches in areas east of these ranges.

(3) Amounts for a given duration that equal or exceed the 100-year precipitation statistic for the corresponding duration at the location of the storm event (Miller et al., 1973).

[b] Data sources for sea surface temperatures: U. S. National Marine Fisheries Service (1960 et seq.), including Figs. 21-22 of this paper; Allison et al. (1972), including Figs. 20 and 26-30 of this paper; Eber et al. (1968); plus indirect evidence from Figs. 23-25 (from Quinn), 31-32 and 34 (from Berlage), and 33 (from Walker and Bliss).

Data sources for storm events (see also original recording charts or observers' records, many of which are on file at the National Climatic Center, Asheville, NC):

A. U. S. Weather Bureau, ESSA, and NOAA (1897 et seq.): month and year of issue same as that of storm event.
B. U. S. Weather Bureau, ESSA, and NOAA (1951 et seq.): month and year of issue same as that of storm event.
C. U. S. Weather Bureau (1931 ff).
D. U. S. Weather Bureau (1960).
E. U. S. ESSA (1966).
F. Weaver (1962).
G. Riedel and Hansen (1972).
H. Hansen (1975b).
I. Leopold (1943, 1944).

Data sources for storm events (cont.):

J. Goodridge (1972a).
K. Goodridge (1972b).
L. Goodridge (1975).
M. Monthly Weather Review: articles for same month and year as that of storm event.
N. Weatherwise: "Weatherwatch" article for issue of two months after storm event.
O. Ludlum (1970-1972).
P. U. S. Corps of Engineers (1940ff); plus various other published and unpublished reports by U. S. Weather Bureau (National Weather Service), U. S. Corps of Engineers, County Flood Control Districts of California, and other agencies.
Q. Langbein (1941).
R. The Morning Call (1889).
S. McAdie (1908).
T. Cornthwaite (1919).
U. Daily News (1914).
V. Sprague (1932).
W. Wing (1933).
X. Pyke (1975).
Y. San Bernardino County Flood Control District (1946).
Z. Kesseli and Beaty (1959).
A′. Nicholas (1958).
B′. San Diego County Flood Control District (1968).
C′. Santa Barbara County Flood Control District (1969).
D′. Richardson (1970).
E′. Ribble (1972).

[c] Temperatures of the extreme northeastern tropical and subtropical Pacific Ocean (off the west coast of California, Baja California, and mainland Mexico):

-- significantly below normal	+ slightly above normal	(no entry) unknown
- slightly below normal	++ significantly above normal	
o near normal	+++ much above normal	

[d] EN = generally accepted El Niño occurrence during the equatorial warming in question (see Table 1 and Figs. 23, 31-32, and 34).
EN? = not generally accepted El Niño occurrence, but some confirming evidence available (see Table 1 and Figs. 23, 31-32, and 34).
M = minor equatorial warming: temperatures only slightly above normal (see Figs. 26-30).
VM = very minor equatorial warming between two periods of below normal equatorial ocean temperatures. Equatorial temperatures probably not much if at all above normal at time of storm event (see Figs. 26-30).

[e] Source M lists "5.10 in. in about one hour." From the Tucson Star (1878): "The storm lasted about 3 hours and rain fell to a depth of 6 inches on the level." There are accounts in the same newspaper article of very extensive flooding in and around Tucson from this, "the most violent rain storm that has occurred in Arizona during the recollection of the oldest settlers..." The University of Arizona station at Tucson reported a total of 5.72 inches of precipitation for the month of July 1878 (U. S. Weather Bureau, 1931ff).

[f] Associated, or apparently associated, with tropical cyclone of same date(s) listed in Table 4.

[g] Ocean temperatures off the west coast of California and Baja California not known, but believed to have remained significantly above normal during the brief, although pronounced, equatorial cooling of 1889-1890 (Figs. 31-34).

[h] Amount somewhat questionable (see Data Sources).

[i] Equatorial ocean temperatures (as implied by Figs. 31-34) were perhaps still near normal or even slightly below normal at the time of the precipitation event. It may have been possible, however, that by the time of this event the tropical and subtropical northeastern Pacific Ocean had begun to warm up in conjunction with an increase in the North Equatorial Countercurrent, which often leads to the development of an equatorial warming (see Wyrtki, 1973; Namias, 1973c; Bjerknes, 1961, 1966b, 1974b; and others).

[j] Equatorial ocean temperatures had, or apparently had, returned to normal or below by the time of the storm event (Figs. 26-30).

[k] No measurements of amounts for durations of less than 1 observational day available, but short-duration intensities believed to have been very high.

[ℓ] Associated with a cool-season type of storm.

[m] From The Morning Press (1914): "During the worst two hours...there was a little more than four inches precipitation."

[n] One-hour amount synthesized by reduction of 24-hour total (8.75 inches) through subtraction of 24-hour amount at a nearby station (Source G).

[o] From Source A: "Within a period of about six hours Redding received a rainfall of more than five inches, while Kennett received over four inches." The 24-hour totals ending on 2 October 1918 were 5.20 inches at Redding and 4.41 inches at Kennett (about 23 miles to the north of Redding).

[p] General precipitation greatly enhanced by orographic uplifting.

[q] Included within this 2-hour precipitation amount is an extreme one-minute burst of rainfall which has frequently been reported as 1.03 inches (Sources J, L, P; U. S. Weather Bureau, 1941; and others). This amount, however, has been questioned by Brancato and Remmele (1946) and others, who feel that because of instrumental problems, the reading of 1.03 inches in one minute is too high, and that the value of 0.65 inches is a better approximation to the true maximum one-minute rate of rainfall which occurred. Either of these two figures, however--whichever one is accepted--represented a world's record precipitation intensity for that duration until broken on 4 July 1956 by 1.23 inches in one minute at Unionville, MD (Source D and others).

[r] Of this amount, 4.34 inches fell within 5 hours (Source W). From Source F: "Description of the flood indicates that the Tehachapi observation did not sample the center of this local cloudburst and that most of the rain fell in a much shorter time interval than stated above."

[s] Despite the cooler Pacific water of this year, the moisture for this precipitation event was most likely imported by a tropical storm (see Table 4) which was sustained to a higher latitude than usual by traveling directly up the warm Sea of Cortez (see Footnote a of Table 4).

[t] Includes 7.24 inches in 5 hours and other exceptional intensities for durations of from 2 to 12 hours (Sources J,L,P).

[u] Equatorial ocean temperatures below normal at the time of the storm event.

[v] A claim that a 12-inch-deep can in nearby Coachella, CA filled and overflowed from rainfall during this storm is not substantiated (Source X).

[w] Amount tabulated here occurred as part of the State of California's record 24-hour precipitation of 26.12 inches (Sources J,L; and others), which also included other exceptional amounts of rainfall for durations of from 8 to more than 48 hours (Sources J,L; U. S. Weather Bureau, 1940-1948; and others).

[x] Included within this 3-hour precipitation are the amounts of 2.70 inches in 1 hour and 1.40 inches in 15 minutes (Sources J,L,P).

[y] Amounts of 3.2 inches in 45 minutes (Source Y) and 3.25 inches in 80 minutes (Source A) are also reported in this storm.

[z] Central value of storm (over unpopulated mountain peaks) is believed to have been considerably higher--approximately 7.5 inches. One station--Ray, AZ--reported 4.05 inches in less than 2 hours, according to a U. S. Corps of Engineers "bucket survey" (Source P). The entire storm amount at Ray all fell within one and one-half hours, according to one local newspaper.

[α] Data Sources J and L list 8.00 inches in 2.5 hours. Source Z (also quoted in Source D) reports that "...more than 8 inches of rain fell in slightly more than two hours on Chiatovich Flat..." Source Z (on another page) also cites "8.25 inches of rain...in approximately two and one-half hours." Sources E and G list 8.25 inches in 150 minutes. Source F mentions "an unconfirmed report of over 8 inches in a little over 2 hours on July 19, 1955 in a portable rain gage near the crest of the White Mountains northeast of Bishop..."

[β] Amounts of "5.25±" inches reported at two gages west of Needles, CA (Source P) are not substantiated. Duration of storm is unknown, but is believed to have been short, as with most desert summer thunderstorms. Severe local flooding was reported in the area (Source P).

[γ] Unsubstantiated estimates of both amount and duration. An amount of 5.0 inches was measured by can (with poor exposure) several miles north of the Gila Mountains and away from the apparent storm center. Widespread flooding was reported in the region (Source P).

[δ] From Source A′: "Another rain gage was located at the San Gorgonio Lodge at Forest Home where the storm may have centered. However, children molested the gage by adding water and the record consequently is lost. Claims have been made that 5 inches of rain fell in an hour's time but this, of course, is not substantiated."

[ε] One measurement in the storm area of 7 inches is considered highly questionable (Source G).

ζ Five-hour amount (10.6 inches) synthesized by reduction of storm total ~~(10.6 inches)~~ through subtraction of storm totals at nearby stations (Source F).

η The equatorial Pacific Ocean, and especially the northeast Pacific Ocean, cooled very slowly following the 1957-1958 warm anomaly (see Fig. 29). The northeast Pacific Ocean was still significantly warmer than normal at the time of the storm event.

θ Includes 3.69 inches in 2 hours and other exceptional intensities for durations of from 1 to 6 hours (Source P).

ι Includes 3.25 inches in 2 hours (Sources B,J,L).

κ Gage overflowed during storm. Record partially synthesized by comparison to adjacent standard and nearby recording gages. This reconstructed record also includes other exceptional rainfall intensities, such as 13.12 inches in 12 hours and 8.33 inches in 6 hours (Source C′). An amount of 7.86 inches in 6 hours listed by Source L for this station and date represents the maximum precipitation for a 6-hour period actually measured from the recording chart prior to overflow.

λ Precipitation resulted from the combination of an early cool-season type of storm with moisture outflow from Tropical Storm Norma located off the west coast of Baja California Sur (see Table 4, plus that table's Data Sources listed for this 1970 tropical cyclone).

μ Amount tabulated here is a part of the 11.40 inches in 24 hours recorded at this station on 4-5 September 1970--an amount which established an all-time State of Arizona record for that duration, nearly doubling the previous record for an observational day of 6.00 inches--recorded at Crown King, AZ in December 1967 (Kangieser, 1970, 1972c; Sellers and Hill, 1974).

ν Amount tabulated here established an all-time State of Utah record for a 12-hour duration, as well as for a 24-hour duration (Source D′).

ξ Duration is an estimate. An amount of 3.85 inches was measured in 80 minutes by a recording gage at a different location (Source P). (See also tabulations and discussion by Kangieser, 1972a.)

ο Source N reports that "Sunflower, AZ had 5.38" in a short time on the 6th..." The official National Weather Service station of Sunflower 3NNW reported 3.29 inches for 6 October and .29 inches for 7 October, with observation times at 6 p.m. (Source A). The reported 5.38 inches is assumed to have been a local thunderstorm embedded within the general precipitation associated with Tropical Storm Joanne (see Table 4).

π Storm includes other exceptional intensities for durations of from 2 to 6 hours (Source P). A claim by a local San Luis Obispo radio station of approximately 5 inches in 2 hours and 10 inches in 6.5 hours has been discounted after a very careful investigation by the U. S. Corps of Engineers of the gage's exposure, and also because of the radio station's reputation for consistently reporting considerably more precipitation than anyone else in the area.

ρ Storm includes other exceptional intensities for durations of from 2 to 6 hours (Source B).

σ Includes 4.6 inches in 3 hours and other unusually high intensities for durations of from 2 to 10 hours (Source B).

Discussion. An examination of Table 3 will show that the greatest majority of extreme single-station precipitation events in the southwestern United States, such as those of 1889, 1890, 1891, 1898, 1911, 1918, 1939, 1941, 1958, and others, have occurred during or very close in time to periods of significant warm anomalies in both the equatorial Pacific Ocean and the ocean off the west coast of California and Mexico. One notable exception is the summer of 1955--a year of considerably below normal eastern Pacific Ocean temperatures (tropical-subtropical and equatorial). Despite the lower water temperatures, this summer was characterized by an unusually strong upper-level high over the United States (MWR Jul-Aug 1955; U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.), with stronger and more frequent easterly wave activity. It was apparently these easterly waves, originating in the Gulf of Mexico, which traveled westward and picked up considerable low-level moisture from the Sea of Cortez (whose water is always very warm during the summer months), that were responsible for the four outstanding 1955 precipitation events cited in Table 3. (Note that three of these four events occurred within a fairly short distance from the Sea of Cortez, and that the other storm (Chiatovich Flat) occurred a few hundred miles northwest of the Sea of Cortez--along the direction of the 700-500 mb wind flow--see Riedel and Hansen, 1972; U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.). The same type of mechanism also appears to have been responsible for the Queen Creek, Arizona storm of 19 August 1954.

Another significant exception is the pair of events which occurred in southern California on 18 July 1922. These two major thunderstorms appear to have been triggered by the passage of an unusually strong cold front (for July), perhaps supported by an abnormally deep upper-level trough.

All of the other major warm-season storm events listed in Table 3, and most of this table's local intensifications within general winter storms (especially those not significantly enhanced by orographic uplift--Footnote p) have occurred in conjunction with at least a minor equatorial ocean warming (measured or implied), with (where known) at least near normal tropical and subtropical eastern Pacific Ocean temperatures.

In addition to the single-station precipitation events listed in Table 3, there have been a number of other very intense local storms of short duration in the southwestern

United States whose total rainfall amounts do not fit Criterion (2) of Footnote a to Table 3, but whose maximum rainfall rates over durations of from a few minutes to an hour or so equal or exceed many of those listed in Table 3 (Data Sources A,B,C,G,H,I,J,K,L,M,N,O,P of Table 3; and others). One such example is the 3.35 inches which fell within 20 minutes at Darwin, CA (in the desert east of the Owens Valley) on 13 June 1967 (Goodridge, 1975). These shorter-duration extreme storms are not as well correlated with the northeastern or equatorial Pacific Ocean temperatures as are those larger and longer storms listed in Table 3. It might be reasoned that these shorter-duration events can rely to a large extent upon local concentrations of precipitable water in the air columns above the measuring station and in its immediate vicinity, and that these smaller, more localized storm cells tend to be more of a truly air mass nature and occur more randomly (as well as more commonly) than the somewhat larger and longer-lasting storms--storms which often occur as part of an organized meso-scale or synoptic-scale disturbance, and which must draw upon a moisture supply from a somewhat larger area than merely the immediate vicinity of the storm center.

(2) Tropical cyclones. It is absolutely no surprise that most of the tropical cyclones which have remained intact sufficiently far north along the west coast of Mexico to have directly affected portions of the southwestern United States with their circulations or remnants thereof have occurred during periods of higher than normal ocean temperatures off the Mexican west coast and, to a great extent, also in the equatorial zone, as can be seen in Table 4.

Table 4: Some Tropical Cyclones Significantly Affecting Portions of the Southwestern United States, 1873-1975

Dates	Name (if any)	a	Point of Landfall[b]	Region of Dissipation[c]	Heaviest Rainfall[d]	e	Data Sources[f]	g	Equatorial Warming[h]
16 Aug 1873		U	unknown	unknown	SW CA	***?	O		1873-1874 M
31 Aug 1889		W?	SW CA?[i]	same[i]	SW CA	**?	H, I	j	1888-1889
12-13 Oct 1889		W	near Monterey, CA?[i]	none[c]	Cn-N CA plus Encinitas, CA[k]	***?	G, M	j	1888-1889
24-26 Jul 1902		X	Mouth, Colo Rvr?[i]	NW AZ?[i]	SW CA[ℓ]	*	B		1902-1903
8-10 Aug 1908		U	unknown[i]	unknown[i]	SW CA-W AZ	**	B, H, I		1907-1908 VM
14-16 Sep 1910		W	Pt. Conception, CA	W NV	SW-Cn CA	**	B, M	m	1911-1912 EN?[m]
29-30 Sep 1911		X	NW Sonora[i]	same[i]	Cn AZ-Cn UT[ℓ]	**	B		1911-1912 EN?
4-5 Oct 1911		X	W Cn Sonora	none[c]	SW CO[k,ℓ]	***	B, D, M, P		1911-1912 EN?
12-14 Sep 1918		W	Santa Cruz, CA[i,n]	Red Bluff, CA[i]	Cn-N CA[k,ℓ]	***	B, F, G		1917-1919 EN?
26 Sep-2 Oct 1918		W	none?[i,o]	unknown[i]	S-N CA[k,ℓ]	**	none[o]		1917-1919 EN?
20-23 Aug 1921		X	NW Sonora?[i]	same?[i]	Cn AZ[ℓ]	**	B, S	-	none[p]
30 Sep-1 Oct 1921		W	NW BCN	none[c,q]	S CA-SW AZ	***	B, G, H, M, T, U	-	none[p]
4-5 Oct 1925		W	NW BCN?[i]	SW ID[i]	S CA-W AZ	***	B, M, P	++	1925-1926 EN
25-27 Sep 1926		X	W Cn Sonora[i]	SE AZ?[i]	SE AZ[ℓ]	***	B, M, P, S	++	1925-1926 EN
6-9 Oct 1926		X	W Cn Sonora	S AZ	SE AZ[ℓ]	**	B, S	++	1925-1926 EN
10-13 Aug 1927		X	NW Sonora[i]	SW UT?[i]	S NV-Cn AZ[ℓ]	**	B, S	o	1927-1928 VM
11-14 Sep 1927		W	NW BCS[i]	same?[i,r]	Cn UT-SE AZ[ℓ]	**	B, M, S, T	o	1927-1928 VM
31 Aug-3 Sep 1929		X	NW Sonora	same	S-Cn AZ	*	B, S	+	1929-1932 EN?
16-18 Sep 1929		E?	SE BCN?[i]	N Cn CA	S CA-W AZ	**	B, H, I, M, U, A′	+	1929-1932 EN?

(table continued on next page)

Table 4 (cont.)

Dates	Name (if any)	a	Point of Landfall [b]	Region of Dissipation [c]	Heaviest Rainfall [d]	e	Data Sources [f]	g	Equatorial Warming [h]
8-10 Dec 1930 [s]		E?	NW Sonora? [i]	same? [i,s]	SW NM	*	B, U	++	1929-1932 EN?
12-14 Sep 1931		E	W Cn Sonora	none? [c]	S AZ [ℓ]	**	B, M, S, B′	++	1929-1932 EN?
23-25 Sep 1931		W	NW BCS	same? [r]	SE AZ-SW NM	*	B, M, B′	++	1929-1932 EN?
26-30 Aug 1932		E	Mouth, Colo Rvr [i]	same? [i]	AZ-NV-UT	*	B, M	-	1929-1932 EN? [t]
28 Sep-1 Oct 1932		E	Mouth, Colo Rvr [i]	SE CA? [i]	Tehachapi, CA [k]	***	F, G, H, M, P, U, V, W	-	1929-1932 EN? [t]
24-27 Aug 1935		W	Pt. Conception, CA	same	Cn CA-S AZ	**	B, M, S	-	1935-1936 M
6-9 Aug 1936		E	Mouth, Colo Rvr	SW ID	S CA-S AZ	**	A, B, H, M, S, C′, D′, E′	o	1935-1936 M
17-19 Aug 1936		W	NW BCS? [i]	same? [i]	SE AZ-SW NM	*	M	o	1935-1936 M
9-12 Sep 1936		E	W Cn Sonora	same	S AZ-SW NM	*	B, M, S	o	1935-1936 M
4-7 Sep 1939		W	NW BCN	NW CO [q]	SE CA-NW AZ	***	B, D, M, P, R	+++	1939-1942 EN
11-13 Sep 1939		X	NW Sonora	NW AZ	W AZ-S UT [ℓ]	***	B, M, R	+++	1939-1942 EN
24-26 Sep 1939		W	Long Beach, CA	SW UT	S CA [k]	****	A, B, F, G, H, I, J, K, L, M, O, P, R, X	+++	1939-1942 EN
12-14 Sep 1941		E	NW Sonora	same	W-Cn AZ [ℓ]	**	B, M	++	1939-1942 EN
21-24 Sep 1941		X	NW Sonora	same	SW NW [ℓ]	*	B, M	++	1939-1942 EN
11-13 Nov 1941		W	NW BCN [i,u]	NW NM [i]	S CA-Cn AZ [ℓ]	***	B, M	+	1939-1942 EN
6-8 Oct 1945		X	Mouth, Colo Rvr	SW AZ [q]	SE CA-S AZ [ℓ]	**	B	o	1945-1946 M
28 Sep-1 Oct 1946		W	W Cn BCN	SW AZ [q]	S CA-S AZ [k,ℓ]	**	B, C, S, Y	o	1945-1946 M
7-9 Sep 1949		W	none	off SW BCN	Cn AZ	*	A, B, C	-	1948-1949 M [t]
26-29 Aug 1951		W	NW BCN [i]	W AZ [i]	Cn AZ	***	B, C, G, H, K, L, M, P, R, S, F′	-	1951 M
24-27 Aug 1953		W	NW BCS	same	S AZ	*	B, C, G, L, M, R, S	o	1953 EN

(table continued on next page)

Table 4 (cont.)

Dates	Name (if any)	a	Point of Landfall [b]	Region of Dissipation [c]	Heaviest Rainfall [d]	e	Data Sources [f]	g	Equatorial Warming [h]
16-18 Jul 1954		W	W Cn BCS [i]	SE BCN? [i,q,r]	Cn AZ	*	B, C, L, R	o	none [p]
12-15 Aug 1957		W	none	off W BCN	Cn-SE AZ	*	B, C, L, M, Q, R, S	++	1957-1958 EN
5-6 Oct 1957		X	W Cn Sonora	SW NM	S-SE AZ	*	B, C, L, M, Q, R	++	1957-1958 EN
28-30 Jul 1958		W	none	off NW BCS	SW-SE CA [k]	*	B, C, E, L, M, Q, R	+++	1957-1958 EN
4-6 Oct 1958		E	NW Sonora	same	E AZ-W NM	**	B, C, E, L, M, Q, R	+++	1957-1958 EN
9-11 Sep 1959		W [v]	W Cn BCN? [v]	same? [v]	S CA-AZ	*	B, C, E, G, L, M, Q, R, S	++	1957-1958 EN [w]
18-22 Aug 1960	Diana	E	W Cn Sonora	same	S AZ [ℓ]	*	B, C, E, L, M, Q, R	+	1960-1961 VM
7-11 Sep 1961	Orla	W	NW BCN	same	Cn-SE AZ	**	B, C, E, G, H, L, M, Q, R, S	-	1960-1961 VM [t]
24-26 Sep 1962	Claudia	X	NW Sonora	same	SW-S Cn AZ	**	B, C, E, H, L, M, P, Q	-	none [p]
16-19 Sep 1963	Katherine [x]	W	NW BCN	SE CA	S CA-SW AZ [ℓ]	***	B, C, E, H, L, M, N, O, Q, G′	++	1963-1964 M
9-11 Sep 1964	Tillie	W	NW BCS	same	SE AZ	*	B, C, E, G, H, L, Q, S	--	none [p]
2-6 Sep 1965	Emily	W	NW BCN	same	Cn AZ-Cn UT	**	B, C, E, H, L, N, Q, S	+	1965-1966 EN
12-15 Sep 1966	Helga	W	NW BCS	NE BCS	S AZ	**	B, C, E, G, H, L, N, Q	++	1965-1966 EN [t]
1-2 Sep 1967	Katrina	X	Mouth, Colo Rvr	same	SE CA-SW AZ	***	B, C, E, H, M, N, O, Q, S	+	none [p]
7-11 Sep 1967	Lily	W	none	off W BCN	Cn-SE AZ	*	B, C, E, H, J, M, N, Q, S	+	none [p]
18-20 Aug 1968	Hyacinth	E	SW Sonora	E AZ?	E AZ	*	B, C, E, M, N, Q	o	1968-1970 M
2-4 Oct 1968	Pauline	X	W Cn Sonora	NE AZ?	NE AZ	*	B, C, E, M, Q	o	1968-1970 M
11-14 Sep 1969	Glenda	W	none	off NW BCS	S-Cn AZ	*	C, E, M, Q, S	+	1968-1970 M
3-6 Sep 1970	Norma	W	NW BCS	same	Cn AZ-SE UT [k,ℓ]	**	A, C, E, G, M, N, P, Q, H′, I′, J′, K′, L′, M′, N′, O′, P′, Q′	o	1968-1970 M [t]

(table continued on next page)

Table 4 (cont.)

Dates	Name	[a]	Point of Landfall[b]	Region of Dissipation[c]	Heaviest Rainfall[d]	[e]	Data Sources[f]	[g]	Equatorial Warming[h]
30 Sep-1 Oct 1971	Olivia	W	NW BCS	SE BCN?[q,r]	NE AZ	*	C, E, M, N, Q	++	1972-1973 EN[y]
28-30 Aug 1972	Gwen	W	none	off W BCN	S AZ	*	C, E, M, N, Q	++	1972-1973 EN
5-6 Sep 1972	Hyacinth	W	none?[z]	off SW CA?[z]	SW CA[ℓ]	**	C, E, M, N, Q	++	1972-1973 EN
6-7 Oct 1972	Joanne	X	Mouth, Colo Rvr	SW AZ	Cn AZ[k]	***	A, C, E, M, N, Q, Q′	++	1972-1973 EN

[a] Trajectory of tropical cyclone northward:

W = west of Baja California peninsula over open Pacific Ocean.

E = east of Baja California peninsula through Sea of Cortez.

X = crossed Baja California peninsula: initial landfall on west coast of peninsula, with trajectory across peninsula, then northward through or across Sea of Cortez to final landfall on coast of mainland Mexico.

U = trajectory unknown.

Note: In the cases of Trajectories E and X the circulation of the tropical cyclone is likely to have been sustained farther north as a result of the cyclone's path over the warm Sea of Cortez than would have been the case over the cooler water west of Baja California, especially during years of cooler than normal water west of the peninsula (e. g., as in 1932 and 1962).

[b] Point of final landfall for storms having trajectory type X. Location abbreviations include: Standard Post Office abbreviations for States and directions; Cn = Central; BCN = Baja California Norte; BCS = Baja California Sur. Note: SW CA refers to coastal southern California; SE CA refers to interior (desert) southern California.

[c] Final dissipation of a recognizable circulation center at the surface (same = same as point of (final) landfall). The storms of 12-13 Oct 1889, 4-5 Oct 1911, 30 Sep - 1 Oct 1921, and perhaps 12-14 Sep 1931 appear to have become active extratropical storm centers which continued northeastward across the entire United States (Sources B, D, G, M, P, U). Several other tropical cyclones listed in this Table, including the late-season storm of 11-13 Nov 1941, may have become extratropical for a short period of time before dissipating. See also Footnotes n and o of this Table.

[d] Areas within the United States only. In many of the storms considerably heavier precipitation is known or believed to have fallen in Baja California or in mainland Mexico (Hastings, 1964a, 1964b; Hastings and Humphrey, 1969a, 1969b; Tingley, 1918; and others).

[e] Impact: A semi-objective assessment by the author of the general impact of the tropical cyclone upon a portion or portions of the southwestern United States (or the potential impact, when over a sparsely populated and/or sparsely gaged region), primarily in terms of area-integrated rainfall, short-duration rainfall intensities, and the general rarity of weather events for the particular portion of the southwestern United States affected. Considered here are only the tropical storm's contributions to the observed meteorological

ADDITIONS TO TABLE 4 SINCE 1975

Dates	Name	a	Point of Landfall[b]	Region of Dissipation[c]	Heaviest Rainfall[d]	e	Data Sources[f]	g	Equatorial Warming[h]
9-10 Sep 1976	Kathleen	W	W Cn BCN	W Cn ID[q]	SE CA	***	C, E, M, N, P, Q	+++	1976 EN
15-18 Aug 1977	Doreen	W	SW CA	same	SE CA	***	C, E, M, N, P, Q	+	1976 EN[t]
26-27 Sep 1977	Glenda	W	NW BCS	same[q]	S-Cn AZ	**	C, E, M, N, Q	+	1976 EN[t]
6-9 Oct 1977	Heather	X	NW Sonora	NE Sonora	SE AZ[l]	***	C, E, M, N, P, Q	+	1976 EN[t]
4-7 Sep 1978	Norman	W	SW CA	same	S-Cn CA	**	C, E, M, N, Q	o	none[p]
			SINCE 1978, ONLY THE MOST PROMINENT STORMS HAVE BEEN ENTERED. A COMPLETE UPDATE WILL BE MADE AT SOME DATE IN THE FUTURE.						
25-26 Sep 1982	Olivia	W	SW CA	same	E Cen CA	**	E, M, N, Q	+++	1982-1983 EN
30 Sep-2 Oct 1983	Octave	W	none	off W BCN	SE AZ	**	E, M, N, P, Q	+++	1982-1983 EN[t]
2-5 Oct 1983	Priscilla	W	none	off W BCN	SW CA	*	E, M, N, Q	+++	1982-1983 EN[t]
31 Oct 1987	Selma	W	SW CA	same	SW CA	**	E, M, N, Q	++	1987 EN

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events--not the effects of any coincident extratropical systems (cold fronts, upper-level troughs, etc.)--to the extent that the tropical and extratropical components can be separated. Emphasis is also placed more upon a tropical cyclone's contribution through direct circulation (i. e., contributions from a storm that has actually moved into, or at least to the edge of, the southwestern United States before dissipating) than merely through outflow from a storm which is dissipating well to the south of Arizona or California.

The impact categories have been assigned as follows:

- * = minor impact: light to moderate rainfall (possibly a few local heavy thunderstorms), or a small area of moderate to heavy rainfall; no prominent direct circulation effects of the tropical cyclone.
- ** = moderate impact: moderate to heavy rainfall over a fairly large area (or very heavy local rainfall), with mostly indirect (outflow) effects from the tropical cyclone; or light to moderate rainfall or small area of rainfall, with some direct circulation effects.
- *** = major impact: generally widespread heavy rainfall, with definite direct circulation effects; or moderate to heavy rainfall, with pronounced circulation effects.
- **** = severe impact: widespread heavy rainfall with some locally extreme intensities, plus very strong direct circulation effects, including sustained surface winds of at least tropical storm intensity (≥35 knots) experienced within areas of the United States.

It should be noted that Tropical Storm "Norma" of 3-6 September 1970, which was associated with the disastrously heavy rains over many parts of Arizona and other States (see Table 3; plus this storm's Data Sources in Table 4), has been assigned only a moderate impact value (**) here because of the fact that the tropical cyclone's direct circulation never entered the southwestern United States (only a massive moisture outflow), and because the primary convergence and orographic mechanisms responsible for the catastrophic precipitation did not result from the tropical storm but instead were part of the unusually intense extratropical storm system that deepened over the southwestern United States during this period (see Data Sources). It is felt that the direct tropical storm circulation itself, without the other components, would likely have produced at the very most a moderate impact upon the southwestern United States.

[f] Rainfall data sources: U. S. Weather Bureau (1931ff), U. S. Weather Bureau, ESSA, and NOAA (1897 et seq.), U. S. Corps of Engineers (1940ff), Leopold (1943, 1944), Ludlum (1970-1972), plus other sources listed under Footnote b of Table 3 when Footnote k of this Table applies.

Sea surface temperature data sources: U. S. National Marine Fisheries Service (1960 et seq.), including Figs. 21-22 of this paper; Allison et al. (1972), including Figs. 20 and 26-30 of this paper; Eber et al. (1968); plus indirect evidence from Figs. 23-25 (from Quinn), 31-32 and 34 (from Berlage), and 33 (from Walker and Bliss).

Tropical cyclone data sources: (see next page).

Data sources for tropical cyclones (Note: To avoid confusion, the designating letter of a source appearing in both Tables 3 and 4 has been kept the same in both Tables. Note also that U. S. NOAA (1973 et seq.) satellite charts are now also available for the charting of tropical cyclones, beginning with the 1973 season.):

A. U. S. Weather Bureau, ESSA, and NOAA (1897 et seq.): monthly summaries of meteorological conditions and events, including "Special Weather Summary" contributions by Hales (1970) and Kangieser (1972b).
B. U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA (1943 et seq.).
C. U. S. Weather Bureau, ESSA, and NOAA (1946 et seq.).
D. U. S. Weather Bureau (1960).
E. U. S. Weather Bureau (now National Weather Service) facsimile weather charts, transmitted from National Meteorological Center, Suitland, MD.
F. Weaver (1962).
G. Riedel and Hansen (1972).
H. Harris (1969).
I. Aldrich and Meadows (1966).
J. Rosenthal (1972)--exclusive of the charts of Tropical Cyclone Tracks in Northeast Pacific (which were reproduced by Rosenthal from Source L).
K. Kalstrom (1952).
L. DeAngelis (1967).
M. <u>Monthly Weather Review</u>: monthly or annual articles summarizing eastern Pacific tropical cyclones, by such authors as Tingley, Hurd, and McDonald (prior to 1942), Denney and Baum (1968 hurricane season et seq.), and others.
N. <u>Weatherwise</u>: issue of 2 or 3 months after storm event. Includes brief mention or discussion of the tropical cyclone and/or depiction of the cyclone on one or more of the daily weather maps appearing in this publication.
O. Ludlum (1970-1972).
P. U. S. Corps of Engineers (1940ff), and various other published and unpublished reports by U. S. Weather Bureau (National Weather Service), U. S. Corps of Engineers, and other agencies.
Q. <u>Mariners Weather Log</u>: annual articles summarizing eastern Pacific tropical cyclones (by various authors).
R. Rosendal (1962, 1963a).
S. Serra C. (1971).
T. Hurd (1929b).
U. Blake (1935).
V. Sprague (1932).
W. Wing (1933).
X. Pyke (1975).
Y. San Bernardino County Flood Control District (1946).
Z. Blake (1929).
A'. Hurd (1929a).

Data sources for tropical cyclones (cont.):

- B′. McDonald (1931).
- C′. Ward (1936).
- D′. Blake (1937a).
- E′. Blake (1937b).
- F′. Carr (1951).
- G′. Erickson and Fritz (1965).
- H′. Attebery (1971).
- I′. Elson (1971).
- J′. Hales (1972).
- K′. May (1971).
- L′. Pyke (1973).
- M′. Roeske (1971).
- N′. Thorud and Ffolliott (1971).
- O′. Thorud and Ffolliott (1973).
- P′. Zimmerman (1971).
- Q′. Sellers and Hill (1974).

[g] Temperatures of the extreme northeastern tropical and subtropical Pacific Ocean (off the west coast of California, Baja California, and mainland Mexico):

-- significantly below normal	+ slightly above normal	(no entry) unknown
- slightly below normal	++ significantly above normal	
o near normal	+++ much above normal	

[h] EN = generally accepted El Niño occurrence during the equatorial warming in question (see Table 1 and Figs. 23, 31-32, and 34).
EN? = not generally accepted El Niño occurrence, but some confirming evidence available (see Table 1 and Figs. 23, 31-32, and 34).
M = minor equatorial warming: temperatures only slightly above normal (see Figs. 26-30).
VM = very minor equatorial warming between two periods of below normal equatorial ocean temperatures. Equatorial temperatures probably not much if at all above normal at time of storm event (see Figs. 26-30).

[i] Existence or trajectory of storm during all or part of its history subject to question. Analyses on daily maps of Sources B, C, and/or E may have missed the tropical cyclone or its location on one or more days (compare analyses and discussions of other sources). It is noted by Source I that the storms of August 1889 and August 1908, both of which involved rain and strong winds in Los Angeles, were probably tropical cyclones, but that they cannot be positively identified as such.

[j] Ocean temperatures off the west coast of California and Baja California not known, but believed to have remained significantly above normal during the brief, although pronounced, equatorial cooling of 1889-1890 (Figs. 31-34).

[k] Includes intense rainfall event of same date(s) listed in Table 3.

[ℓ] Tropical cyclone or its outflow interacted with a cold front and/or a deep upper-level low moving across the southwestern United States from the west, northwest, or north. Precipitation in some areas was likely induced partly and perhaps largely by the extratropical system. In the case of the somewhat questionable tropical cyclone of 26 Sep - 2 Oct 1918, such an interaction (if it occurred at all) likely took place over the ocean off the northern California coast (see Footnote o of this Table).

[m] Equatorial ocean temperatures (as indicated or implied by Figs. 28, 30, and 31-34) were perhaps still near normal or below normal at the time of the September 1910 tropical cyclone. It may have been possible, however, that by the time of this event the tropical and subtropical northeastern Pacific Ocean had begun to warm up in conjunction with an increase in the North Equatorial Counter-current, which often leads to the development of an equatorial warming (see Wyrtki, 1973; Namias, 1973c; Bjerknes, 1961, 1966b, 1974b; and others).

[n] Likely the farthest northward landfall along the west coast of North America by any tropical cyclone in history (see Source F). A storm off the mouth of the Columbia River on 26 August 1941 may have originally been a tropical cyclone (see Discussion following this Table), but even if so, it is likely to have become extratropical by the time it neared the Oregon-Washington coast. The famous "Columbus Day" storm of 12 October 1962, which brushed by the entire Pacific Northwest coast from Cape Mendocino, CA northward to central Vancouver Island, bringing extreme winds (well over 100 miles per hour) to many areas (see Decker et al., 1962; Namias, 1963; Rosendal, 1963b; Ludlum, 1970-1972; MWR Jan 1963; and others), is also unlikely to have been totally tropical in nature at the time of its Vancouver Island landfall, despite some claims to this effect. See also Footnotes o and ℓ of this Table.

[o] No tropical cyclone is charted on any weather maps or mentioned by any known sources. The weather patterns of California during this period, however, unmistakably indicate the strong influx across the region of a distinctly tropical air mass: the spreading of clouds and moderate rain showers over the length of the State from south to north, along with a warm, and warming, humid air mass, all culminating in the violent thunderstorm activity over the northern portions of the State on the night of 1 October (see Table 3 and Source A). These weather patterns could have possibly resulted from the dissipation of a tropical storm just to the south of southern California, or--perhaps even more likely--from the northward movement of such a tropical storm offshore along a path somewhat similar to that of its 12-14 September predecessor, but far enough at sea to escape detection by the wind and pressure fields at coastal stations. It seems possible that the northward-moving frontal wave appearing off the northern California and Oregon coast on the weather maps of Source B for 30 September and 1 October 1918 could be this tropical cyclone as it was becoming extratropical. (See also Footnote ℓ of this Table.)

[p] Equatorial ocean temperatures below normal at the time of the storm event.

[q] Cyclone circulation may have been sustained somewhat even after moving onshore in Baja California by moisture from the warm Sea of Cortez.

[r] Remnants of cyclone circulation may have drifted intact across Baja California peninsula, the Sea of Cortez, and perhaps northwest Sonora, toward southwest Arizona.

[s] Apparently the latest tropical cyclone ever to directly affect the western United States--if the interpretations of Blake (Source U) are correct that the tropical storm of 7-8 December 1930 known to exist near the mouth of the Sea of Cortez did indeed move northward to near the southern border of Arizona (or perhaps New Mexico) before completely dissipating.

[t] Equatorial ocean temperatures had, or apparently had, returned to normal or below by the time of the storm event (Figs. 26-30).

[u] The storm which appeared over northern Baja California Norte on the morning of 12 November 1941 and moved across Arizona on 13 November (Source B), producing significant surface winds and unseasonably warm rains over most of southern California and Arizona during this period, appears very likely to have been the late-season tropical storm which is shown on the maps of Source B as moving northwestward several hundred kilometers southwest of southern California and dissipating at sea on 10 and 11 November. This storm (much like Tropical Storm Jennifer-Katherine of September 1963--see Footnote x and Source G′) appears to have been lost in the data void at sea while recurving northward and moving into northwestern Baja California Norte.

[v] Center of cyclone apparently crossed portions of the Baja California peninsula at least twice before its final landfall and dissipation--probably along the west coast of north central BCN (Sources B, C, E, G, L, M, Q, R, S). The circulation of this storm, including its eye, appeared to be breaking up along the Baja California coast at the time of this landfall (according to Source Q). Some fragments of this circulation, however, appear to have drifted northwestward into coastal southern California over the next 24 hours (Sources C and E, plus the author's own records and recollections of the meteorological events of those dates).

[w] The equatorial Pacific Ocean, and especially the northeast Pacific Ocean, cooled very slowly following the 1957-1958 warm anomaly (see Fig. 29). The northeast Pacific Ocean was still significantly warmer than normal at the time of the storm event.

[x] Source G′ demonstrates that Tropical Storm Katherine was actually the same tropical cyclone earlier referred to as Jennifer (which was believed to have dissipated at sea several hundred kilometers to the southwest, but which instead recurved northward and crossed the Baja California coast south of Ensenada). (See also discussion of Source Q; compare also the storm of 11-13 November 1941 and Footnote u of this Table.)

[y] Equatorial ocean on the whole was beginning to warm up by the time of the storm event, but the sea surface was still cooler than normal in several portions of the eastern equatorial Pacific at the time of the storm event.

[z] Source M shows the remnants of this cyclone (in a dissipating depression stage) as moving onshore just north of San Diego and continuing northeastward into the interior of southern California. This would seem likely to have been only the upper-level cloud mass (as viewed from satellites), since the circulation at the surface appeared to have dissipated off the coast of San Diego (Sources C, E).

Discussion. It is most likely no coincidence that the most intense and most destructive tropical cyclone ever to directly affect the southwestern United States--that of 24-26 September 1939--occurred near the beginning of probably the most prominent north and equatorial eastern Pacific warm anomaly and El Niño of at least the 20th Century, and that during this unusual warm ocean period of 1939-1942 no less than five other tropical cyclones also traveled far enough north to directly and significantly affect portions of the southwestern United States (three of them with major impact). In four of the six cases during this 1939-1942 period, including the unusually late-season storm of 11-13 November 1941, the centers of the cyclones appear to have moved well northward into Arizona, New Mexico, Utah, or even Colorado before dissipating.

Also during this highly anomalous period of years there was a tropical storm of 22-26 August 1941 which recurved northward in the Pacific some distance off the west coast of the United States and survived all the way to at least 40N, 147W (according to the daily maps of U. S. Weather Bureau, Air Weather Service, ESSA, and NOAA, 1943 et seq.) before running into a cold front on 25 August and either dissipating or perhaps becoming extratropical and ending up the next day as a warm-rain-producing frontal wave near the mouth of the Columbia River.

Another period of major warm anomalies in the equatorial and probably also the northeast Pacific Ocean was that of 1888-1892 (see Bjerknes, 1961; Schott, 1933; Eguiguren, 1894). Although in the equatorial zone two distinct anomalies occurred, separated by an apparent marked cooling, the outstanding weather events and patterns of August, October, and December 1889, and August 1890 (see Tables 3 and 4, plus earlier discussion of the 1889-1890 rainfall season) would indicate that the northeast Pacific Ocean likely remained significantly warmer than normal throughout the entire period. Not only were there probably at least two tropical storms which moved onshore in California during the summer and early fall of 1889 (one of which was probably of major potential impact, and which apparently had its landfall as far north as near Monterey), but the reports of cloudbursts in the Los Angeles area during late October and mid-December of 1889 (MWR; U. S. Corps of Engineers, 1940ff) also indicate the likelihood of a warm ocean off the coast during that period and just possibly the entrainment of the remnants of some uncharted late-season tropical cyclones. It is also possible that the extreme storms of Palmetto, Nevada in August 1890 and Campo, California in August 1891 (see Table 3) may have occurred in part as the result of outflow from active or dissipating tropical storms located somewhere in the data void near or off the coast of Sonora or Baja California. The period of 1888-1892, therefore, appears likely to have experienced one of the greatest warm anomalies of record over not only the equatorial Pacific but perhaps also the northeastern Pacific Ocean--possibly even exceeding that of 1939-1942 in magnitude, extent, and duration.

Several of the other tropical cyclones listed in Table 4 as having had a major impact (or potential major impact) upon the southwestern United States also occurred during periods of significantly above normal eastern equatorial Pacific Ocean temperatures, as well as above normal northeastern Pacific Ocean temperatures (where known). These include the storms of 4-5 October 1911, 12-14 September 1918, 4-5 October 1925, 25-27 September 1926, 16-19 September 1963, and 6-7 October 1972. The storm of 16 August 1873, listed as having a possible major potential impact upon the southwestern United States, apparently occurred during a minor equatorial warming (see, e. g., Fig. 34), but the data from this early period are insufficient to make an adequate assessment of conditions.

Of the remaining major-impact storms of Table 4--those of 30 September - 1 October 1921, 28 September - 1 October 1932, 26-29 August 1951, and 1-2 September 1967--three (those of 1921, 1932, and 1951) occurred during periods of apparently below normal temperatures in the extreme northeastern subtropical Pacific Ocean, and three (1921, 1932, and 1967) occurred during marginally (1932) or significantly (1921, 1967) below normal equatorial ocean temperatures. The 1932 storm traveled northward directly up the nearly always warm Sea of Cortez. Hurricane Katrina of 1967 occurred during below normal equatorial temperatures but at least slightly above normal northeastern Pacific Ocean temperatures. This storm also crossed Baja California and traveled up the Sea of Cortez during the latter portions of its trajectory, thereby remaining alive to a higher latitude than most tropical cyclones. The major-impact storms of September-October 1921 and August 1951 appear to have been somewhat unique in that they reached as far north as northwestern Baja California Norte without dissipating completely, even with northeast Pacific Ocean temperatures a degree or two below normal (the equatorial ocean was somewhat warmer than normal during August 1951). The rather high initial intensities of these storms (Hurd, 1929b; Carr, 1951; and others), coupled with quite rapid northward movements over paths fairly close to the west coast of Baja California (Riedel and Hansen, 1972; and others)--and hence over water that is normally warmer than that in the core of the California Current farther to the west--are likely to be factors which helped to sustain these storms to latitudes higher than those at which they would normally be expected to dissipate under the ocean temperature conditions that existed in 1921 and 1951.

Of the remaining tropical cyclones listed in Table 4 (all having only minor or moderate impact upon the southwestern United States) a substantial majority occurred during periods of from slightly to much above normal northeast Pacific Ocean temperatures (most of these also associated with equatorial warm anomalies). The rest of these are divided between near normal northeast Pacific temperatures (with generally minor to very minor equatorial warmings) and slightly below normal northeast Pacific temperatures (usually with below normal equatorial temperatures). Only one tropical cyclone listed in Table 4 (the minor-impact "Tillie" of September 1964) occurred during significantly below normal northeastern Pacific Ocean temperatures (symbol: --), and its landfall and dissipation occurred over Baja California Sur (the southern half of the peninsula).

Wet Summers and Wet Winters

It has been shown thus far that during periods of weakened trade winds and higher than normal eastern equatorial Pacific Ocean temperatures, there is a strong tendency for the Pacific Ocean off the west coast of California and Mexico to also be warmer than normal. Partly because of the weakening (and perhaps northward displacement) of the trade winds, and partly because of the warmer northeastern Pacific water itself, tropical activity over the subtropical latitudes in this part of the globe appears to increase during these periods of oceanic warming. This in turn increases the tendency for convective precipitation in the southwestern United States during the summer and early fall months and increases the chances that a tropical storm will move far enough north along the west coast of Baja California or through the Sea of Cortez to spread heavy, general rainfall over sizable portions of Arizona and other southwestern States.

Since the phenomenon of equatorial warm anomalies often tends to last over a large part of a year and sometimes considerably longer (see Figs. 23-34 and Table 1), it would appear reasonable to expect that: Wetter than normal summer and early fall seasons, the occurrence of tropical cyclones having significant or major impact upon the southwestern United States, and a generally higher potential for local and general warm-season flooding in this part of the country should often tend to occur shortly before or shortly after winters of the type experienced in 1940-1941, 1957-1958, and 1972-1973--i. e., winters characterized by a persistent repetition of moderately heavy storms with intermediate snow levels.

This consideration would appear to have a possibly significant impact upon the design and operation of multi-purpose reservoirs and systems of reservoirs. Of special concern would be the occurrence of a major and prolonged oceanic warming, such as that of 1939-1942 and perhaps those of 1888-1892 and 1911-1915 (the latter two of which were each double-peaked in the equatorial zone but very possibly consisted of a broad, single peak in the northeastern Pacific). For if an abnormally wet summer, complete with one or more tropical cyclones of significant to major (or possibly even severe) impact, were to be sandwiched between two 1940-1941 type winters, the accumulation of water in these reservoirs and systems by the latter part of the second winter season could, under certain conditions, leave rather little storage space for flood control in the event of rapid snow melt and/or significant spring rains (as have occurred a number of times toward the end of such a warm-ocean winter--cf., 1891, 1905, 1912, 1926, 1941, 1958, and 1973).

A potentially even more serious threat to multi-purpose reservoirs and reservoir systems could perhaps develop if, by chance, there would happen to be a sudden onset of rapid equatorial upwelling and cooling beginning around September or October of some year following a pronounced warm oceanic anomaly of at least two years' duration. If such an equatorial cooling were to continue into the Northern Hemisphere winter season, it could (according to earlier discussions) act to favor the generation and maintenance of a large blocking high in the northeastern Pacific. If temperature configurations in the north central and northeastern Pacific Ocean were also favorable for the building and sustenation of such a high-amplitude ridge, then there would exist the possibility that a meteorological pattern somewhat similar to that of January 1969, December 1955 - January 1956, or even January 1862 could follow in sequence a winter such as that of 1940-1941 and an unusually wet summer and fall. Fortunately the occurrence of such a combination of patterns, especially one having 1940-1941 and 1862 magnitudes, would be extremely rare, but this points out that such a type of sequence is at least possible, and that it may perhaps occur with somewhat less severe intensities several times within a century (e. g., such as in Arizona in 1904-1906).

CONCLUSIONS; ATTEMPTS AT SEASONAL PREDICTIONS

It has been seen how in several different ways the temperatures of the eastern equatorial Pacific Ocean can, through atmospheric teleconnections, affect the weather patterns of the southwestern United States and other regions during the cooler portions of the year. It has also been demonstrated how the equatorial ocean temperatures, through their connections with the general trade wind systems of the atmosphere and through their correlations with the temperatures of the extreme northeastern tropical and subtropical Pacific Ocean, can be associated indirectly with the occurrence of tropical cyclones, extreme local storms, and generally heavier than normal precipitation in the southwestern United States during the warmer seasons. Because of the frequent persistence of equatorial warm and cool ocean anomalies over several seasons, it appears possible to link the occurrence of certain meteorological events during one portion of the year with the likelihood of certain events during other seasons.

The type of seasonal pattern which appears to be the most clear-cut and most easily predicted is the one first noted by Dr. J. Bjerknes, in which a substantially warmer than normal ocean over the eastern Pacific equatorial zone gives rise to a strong subtropical jet stream and a repeated series of Pacific cyclones that march across the southwestern United States, dropping abundant precipitation over large areas. Under most circumstances, if such a well-marked equatorial warm anomaly has become thoroughly established by the Northern Hemisphere fall season of any year, it can be predicted with reasonable confidence that the storm patterns of the following mid- and late winter will quite likely be of this general type.

It can also be predicted with considerable accuracy that if the northeastern tropical and subtropical Pacific Ocean is significantly warmer (or, conversely, cooler) than normal, the likelihood of above normal summer and early fall precipitation, a larger number of severe local storms and flash floods, and especially the occurrence of a significant or major impact in the southwestern United States by a tropical cyclone, is also substantially increased (or, respectively, decreased). Because of the relationships between northeastern and equatorial Pacific Ocean temperatures, there can even be some prediction skill in the association of wet winters of the warm equatorial type with the occurrence of generally heavier rainfall and an increased likelihood of flash flooding and tropical cyclones during preceding or following summers; and conversely, in the association of cool-equator winters with a tendency for generally drier summers and for decreased flash flooding and tropical cyclone activity.

Perhaps the most complicated result of equatorial ocean temperature anomalies and trends, and probably the most difficult to predict, is the assortment of high-amplitude ridge-trough patterns that can develop in the atmosphere over the north Pacific Ocean during periods of below normal or rapidly dropping equatorial ocean temperatures. Not only is a high-amplitude regime less of a certainty as a result of a cool or cooling equator than a strong subtropical jet stream is as the result of a warm equatorial ocean, but the number of possible weather patterns over the southwestern United States resulting from such a high-amplitude regime covers virtually the entire spectrum of both temperature and precipitation--from very cold to very warm and from totally dry to exceedingly wet--depending upon the exact locations and configurations of these high-amplitude features. The tendency for high-amplitude patterns to move and to break down and perhaps redevelop more easily than quasi-zonal patterns of the warm equatorial winter type also complicates the predictability of such features as blocking highs and cut-off lows. These atmospheric patterns of large amplitude, especially their all-important positions and configurations, also appear to be significantly more sensitive to the input of energy from the north Pacific Ocean (and consequently to its temperature anomalies) than are strong subtropical jet streams. Therefore any attempts to predict (even in the gross sense) monthly or seasonal weather patterns in the southwestern United States during periods of equatorial cool anomalies or rapid coolings must also rely very heavily upon a knowledge of the surface (and even the subsurface) temperatures over the entire north Pacific Ocean (at the present time a very difficult if not impossible task because of observational sparsities) and upon the application of the ocean-atmosphere relationships in the north Pacific that have been, and are continuing to be, developed by Dr. J. Namias and others.

Seasonal prediction is still in its infant stages. Only a few rather general statements about mean conditions and the possibilities of certain events (such as floods, tropical storms, etc.) can be attempted at this time. But through the pioneering work of the late Dr. Bjerknes and the continuing and very promising efforts of Namias, Quinn, and others, the foundations have been laid, and the way is being paved, toward the development of seasonal forecasting into a viable and working applied science. Considerably more research will be needed in the future in order to further perfect the techniques of this science, and the collection of considerably more extensive and more accurate oceanic and atmospheric data will also be needed in order to properly apply these techniques.

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LIST OF ILLUSTRATIONS

Figs. 35-38	Sea surface temperatures, eastern Pacific Ocean ($^{\circ}F$): maximum (values within each one-square-degree grid which exceed 97.5% of all observed values within that grid for the month in question) and minimum (values within each one-square-degree grid which exceed 2.5% of all observed values within that grid for the month in question) (from Laviolette and Seim, 1969).
Fig. 35	Maximum sea surface temperatures, February.
Fig. 36	Minimum sea surface temperatures, February.
Fig. 37	Maximum sea surface temperatures, November.
Fig. 38	Maximum sea surface temperatures, December.

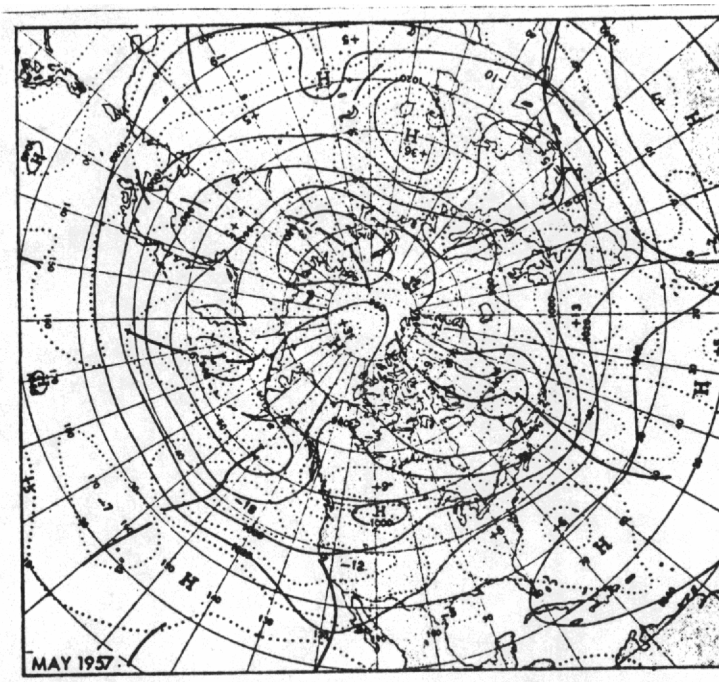
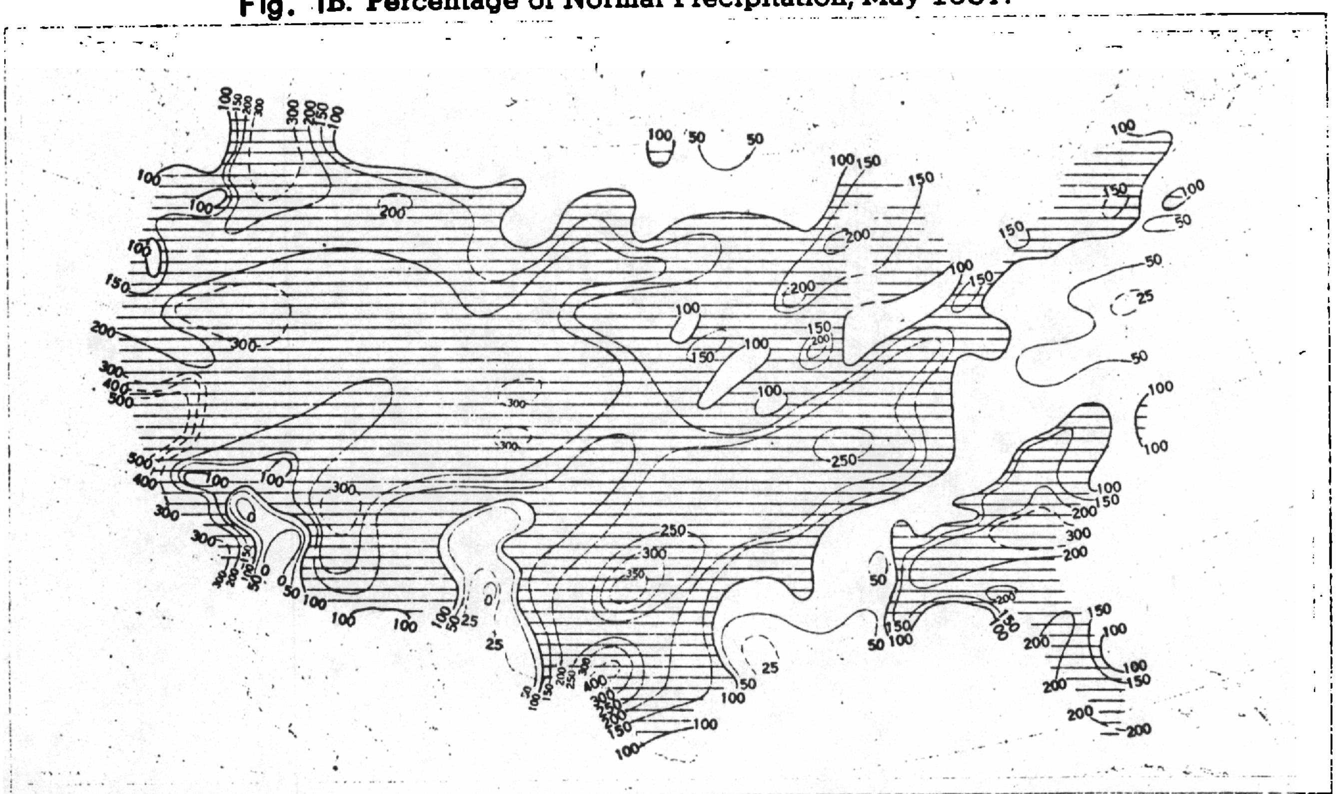


FIGURE 1a–Mean 700-mb. contours and height departures from monthly normal (both in tens of feet) for May 1957. Cyclonic conditions and subnormal heights in western United States and anticyclonic conditions and above normal heights in the East combined to produce widespread heavy precipitation and severe weather.

Fig. 1B. Percentage of Normal Precipitation, May 1957.



Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

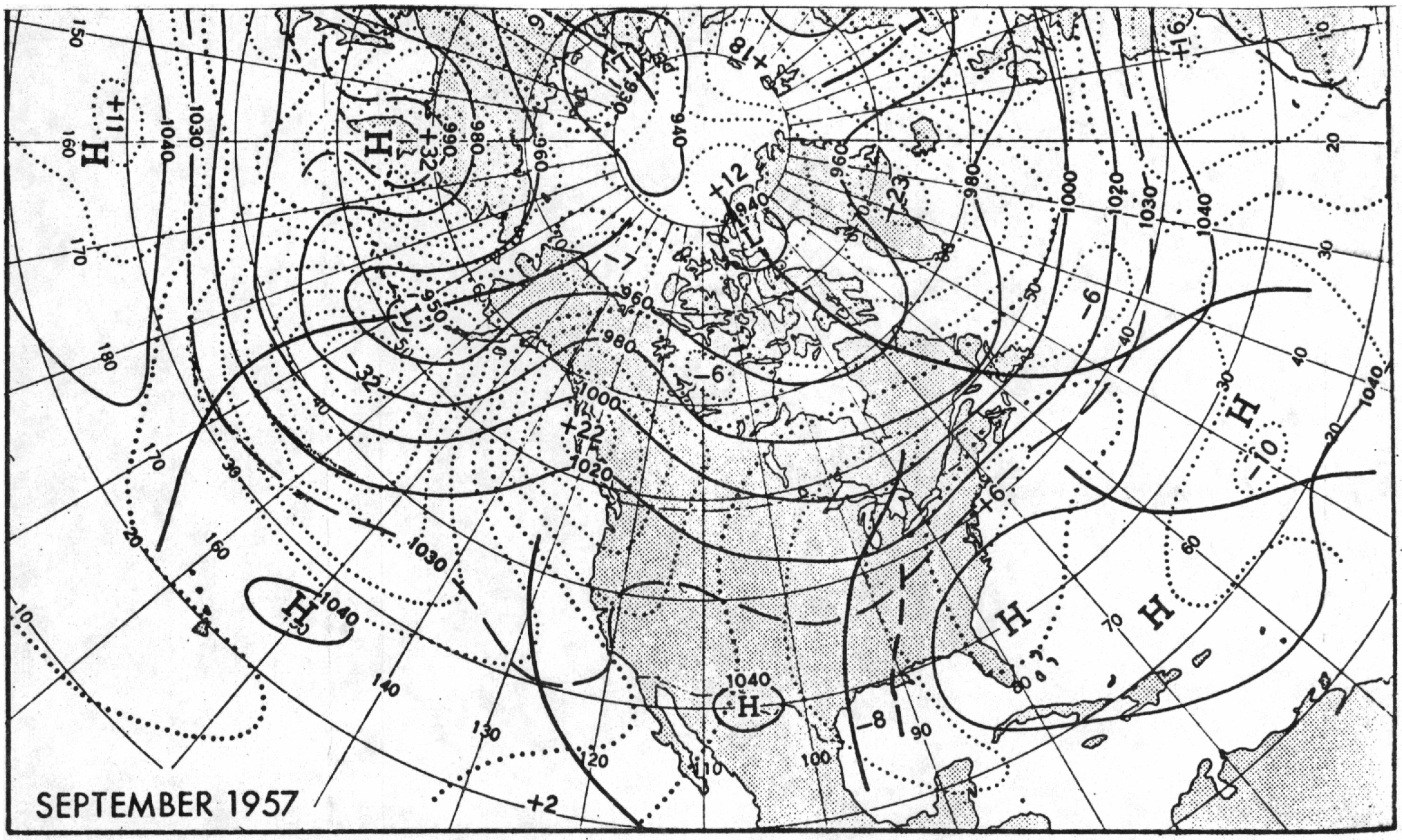
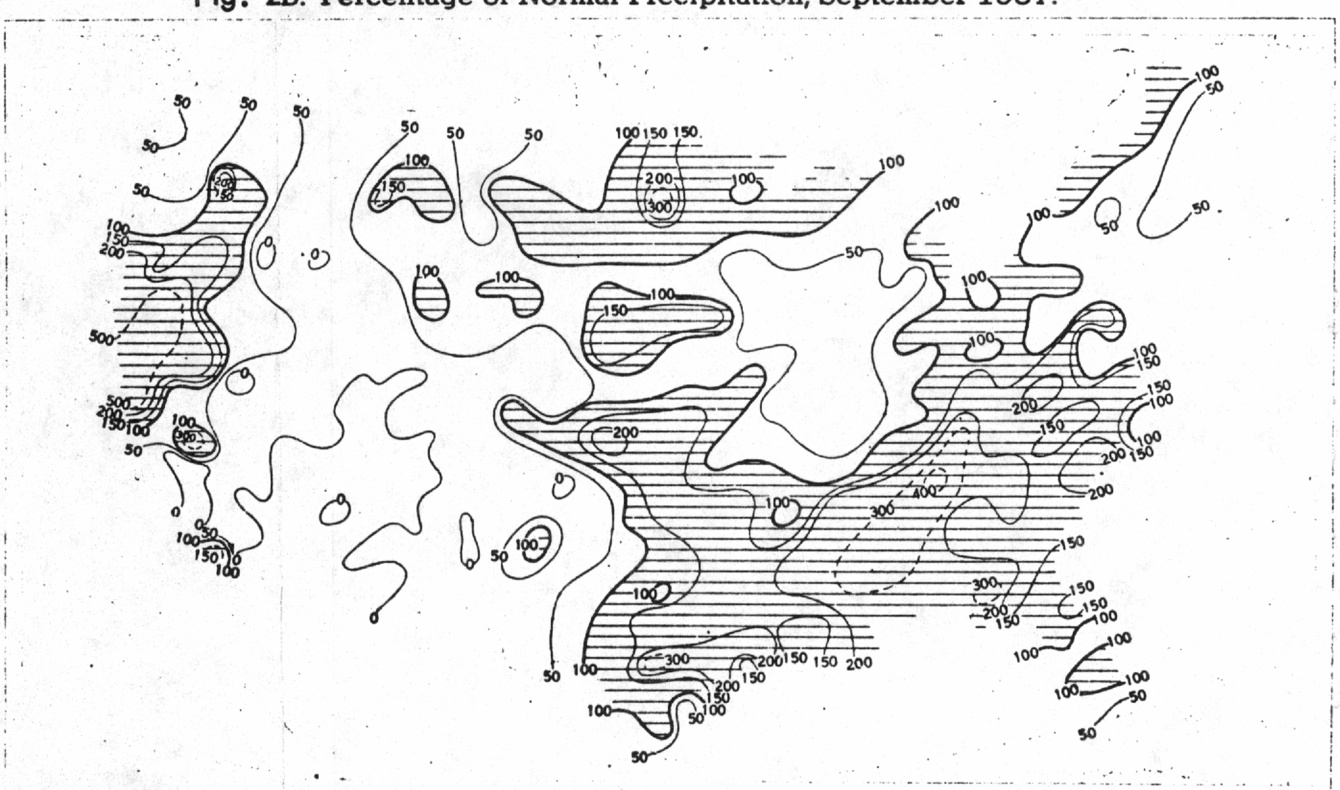


FIGURE 2a—Mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for September 1–30, 1957. Troughs for September are indicated by heavy vertical lines; position of trough in the Southeast in the period mid-August to mid-September is indicated by a heavy dashed line. Dominant feature in the United States was the mean trough in the Mississippi Valley.

Fig. 2B. Percentage of Normal Precipitation, September 1957.



Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

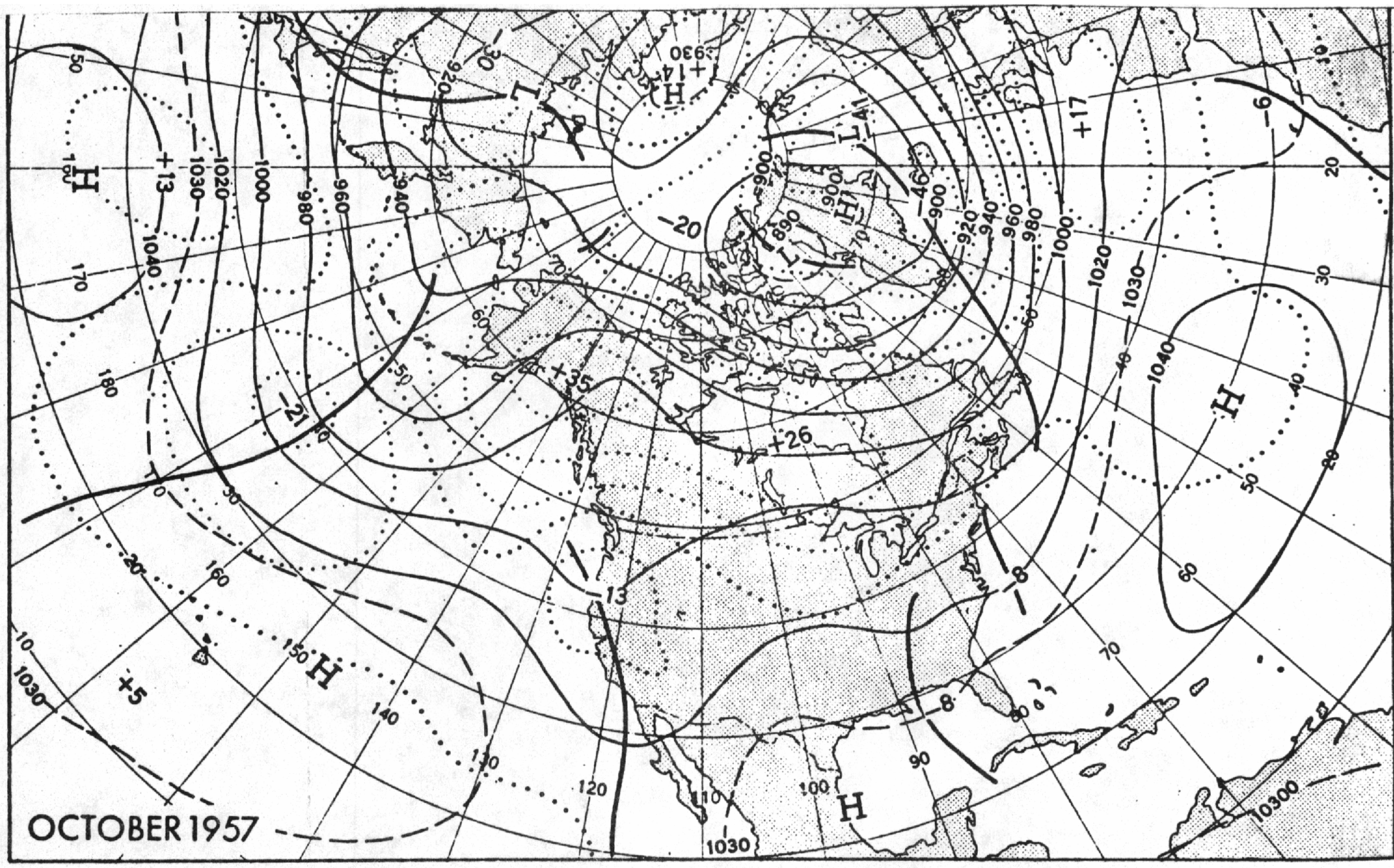
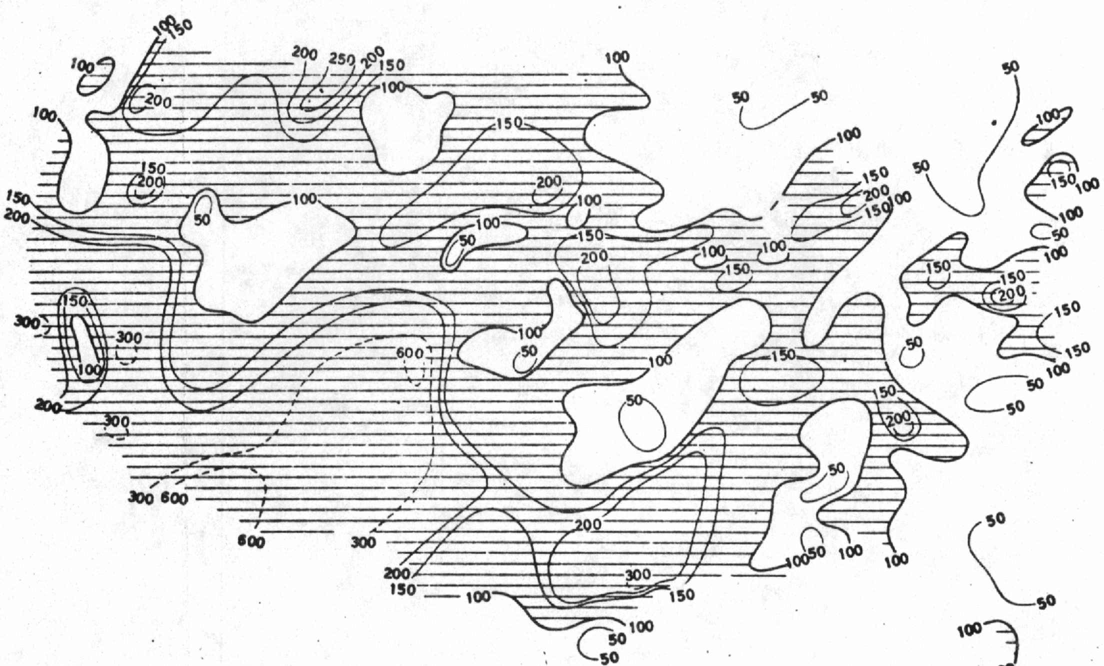


FIGURE 3a—Mean 700-mb. contours (solid) and departures from normal (dotted) (both in tens of feet) for October 1957. Note the difluent nature of the westerly current emanating from the Central Pacific and the blocking character of the DN field over North America, with resultant weak westerlies over the United States.

Fig. 3B. Percentage of Normal Precipitation, October 1957.



Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

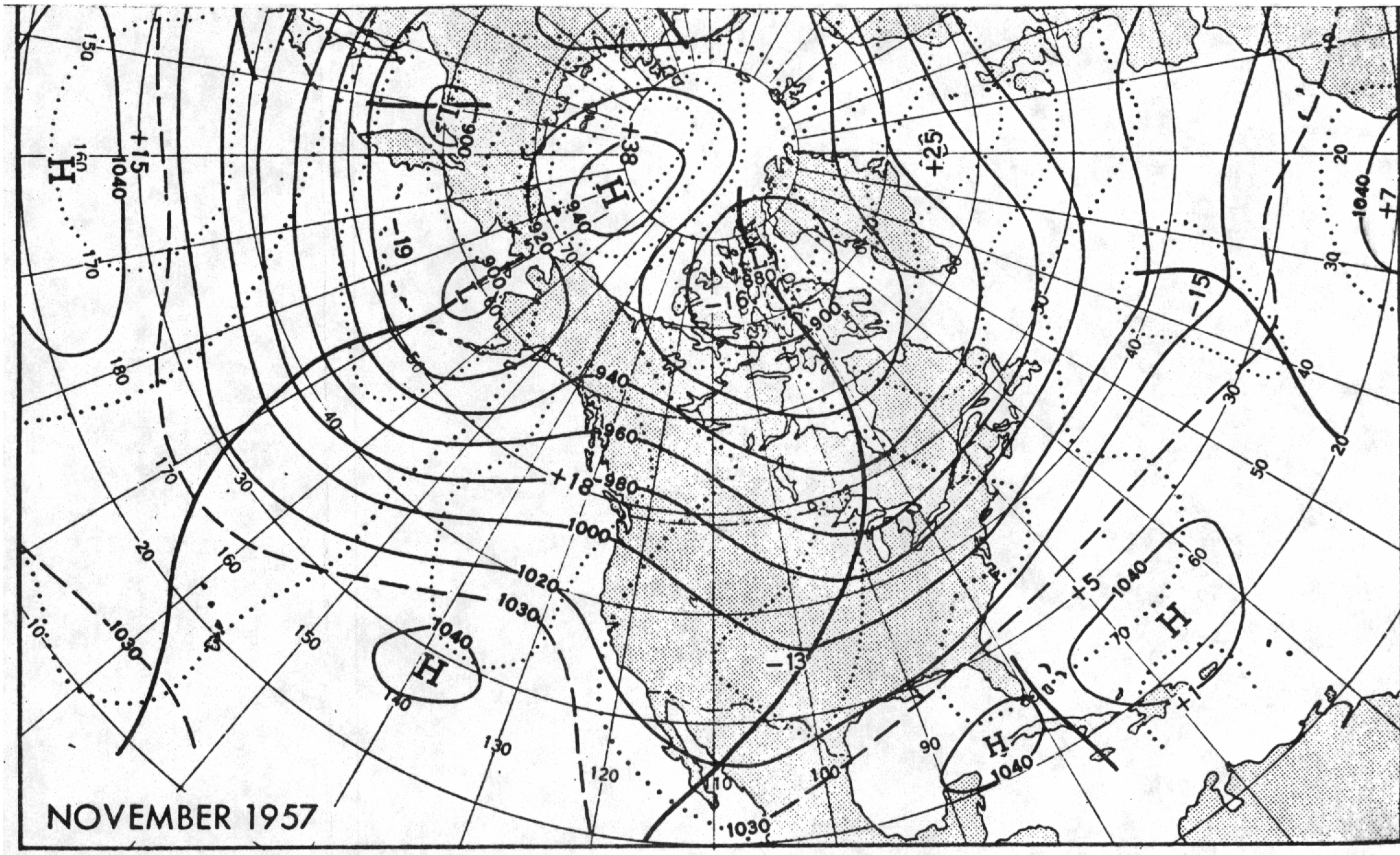
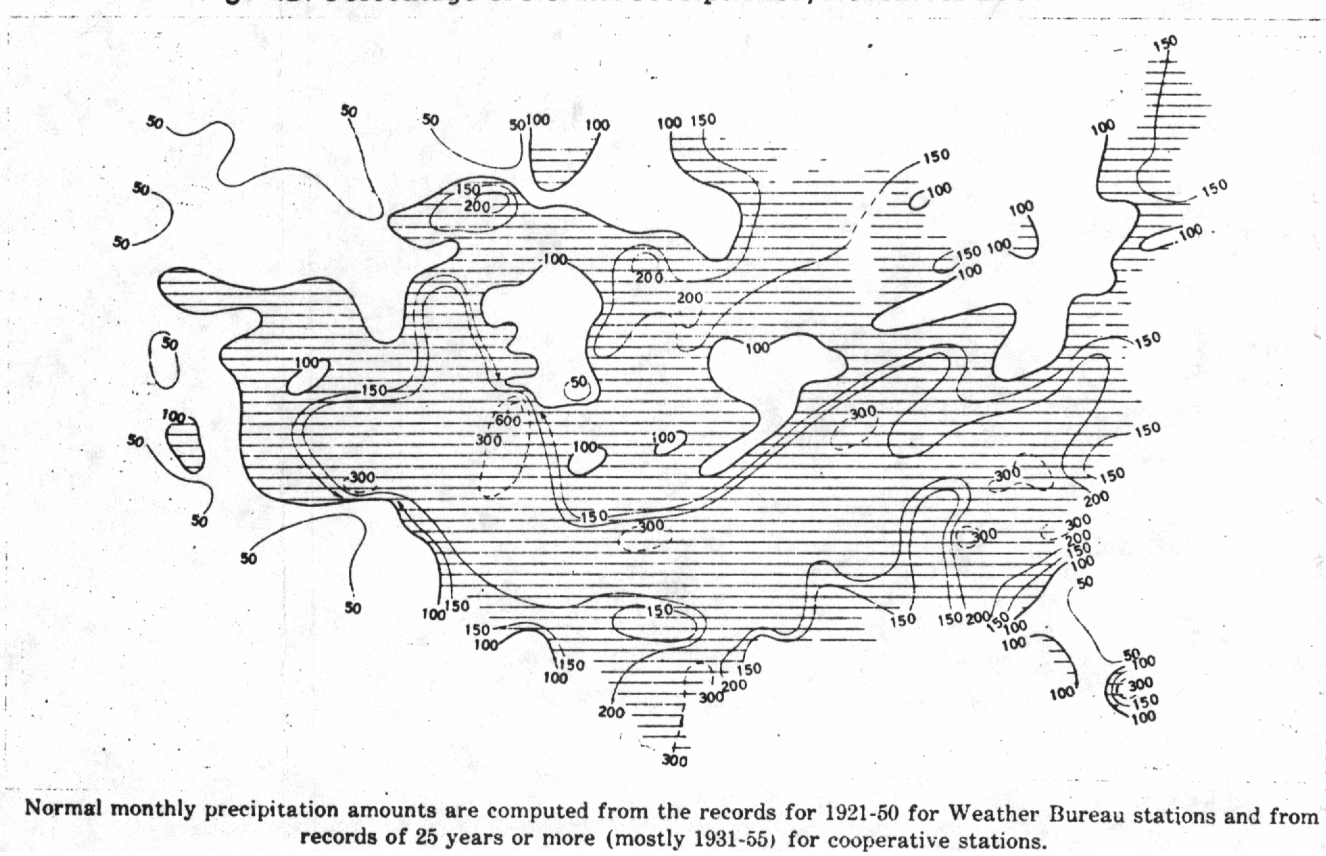


Figure 4a—Mean 700-mb. height contours (solid) and departures from normal (dotted) (both in tens of feet) for November 1957. A deep full-latitude trough (heavy vertical line) occupied central North America, with heights below normal over most of the United States and central Canada. Blocking was active over the northern Atlantic and over the polar basin north of the Bering Strait.

Fig. 4B. Percentage of Normal Precipitation, November 1957.



Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

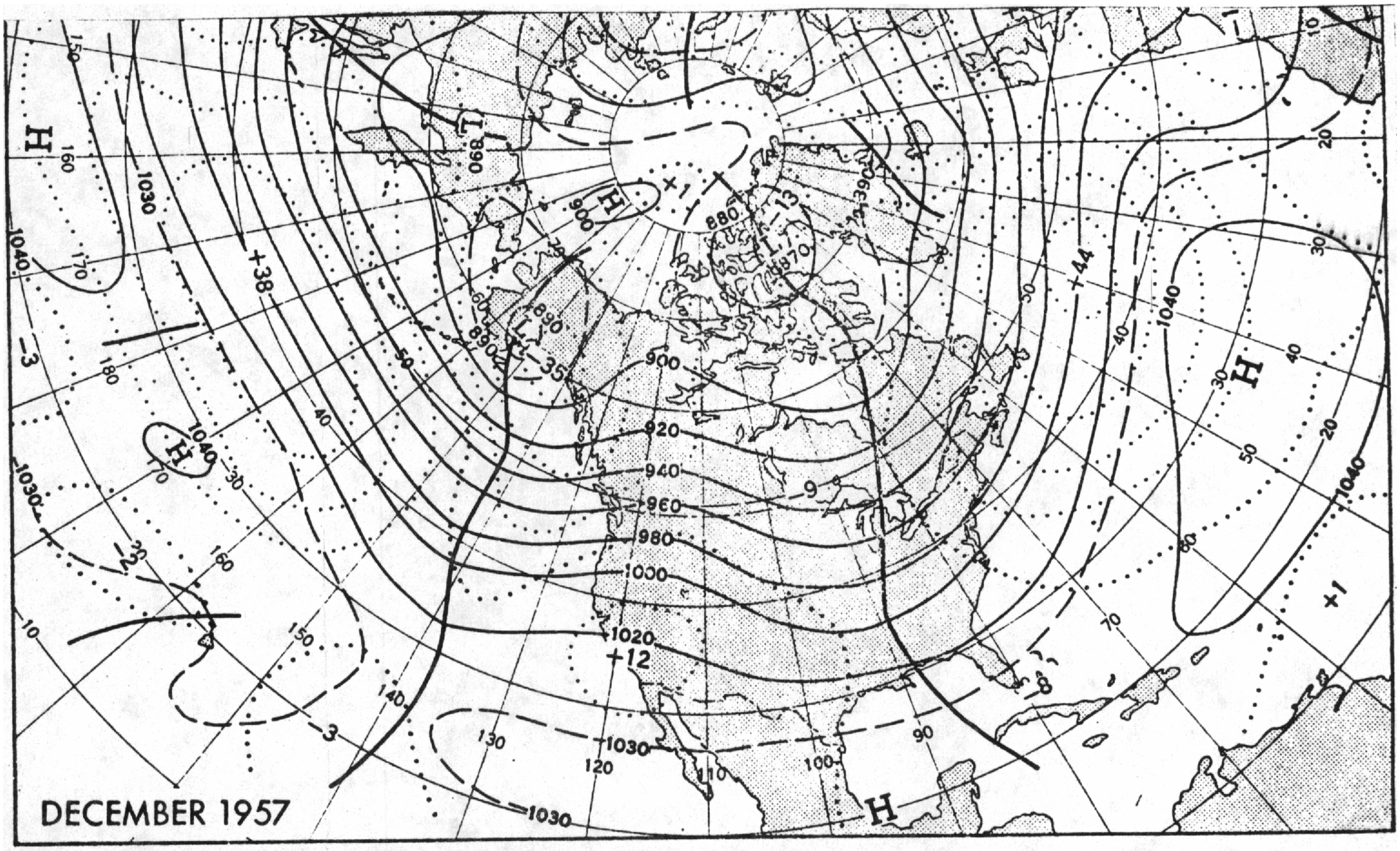
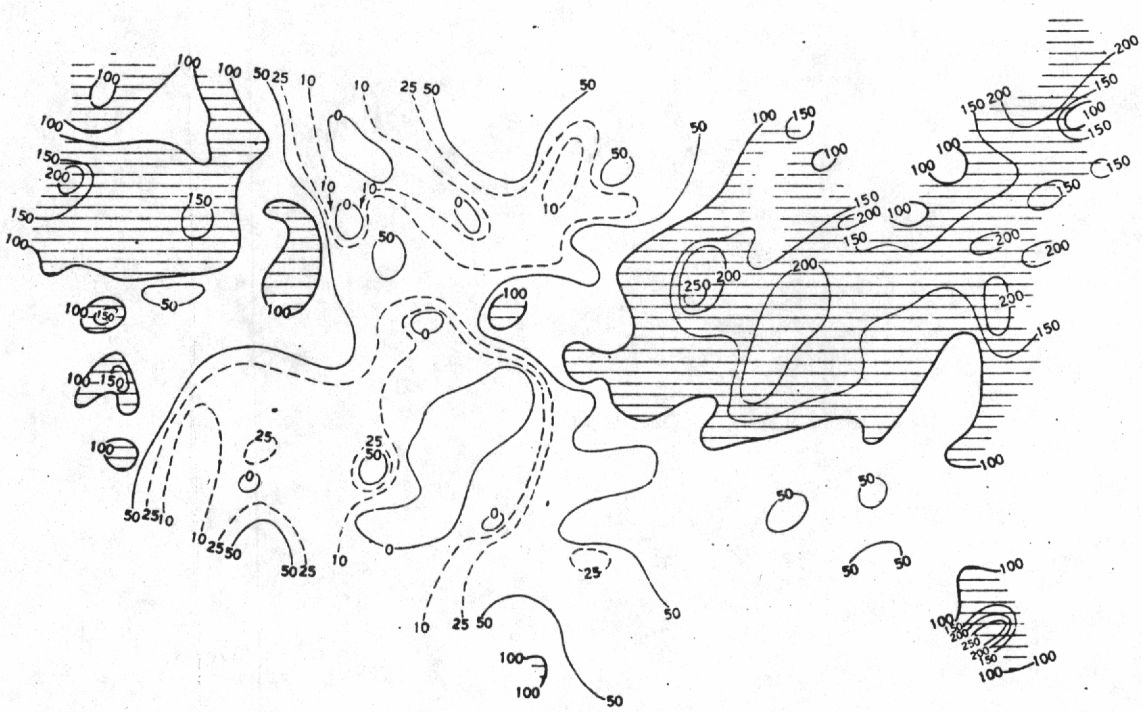


FIGURE 5a-Mean 700-mb. contours (solid) and height departures from monthly normal (dotted) (both in tens of feet) for December 1957. Fast, westerly, small-amplitude flow, typical of high index, prevailed this month.

Fig. 5B. Percentage of Normal Precipitation, December 1957.



Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

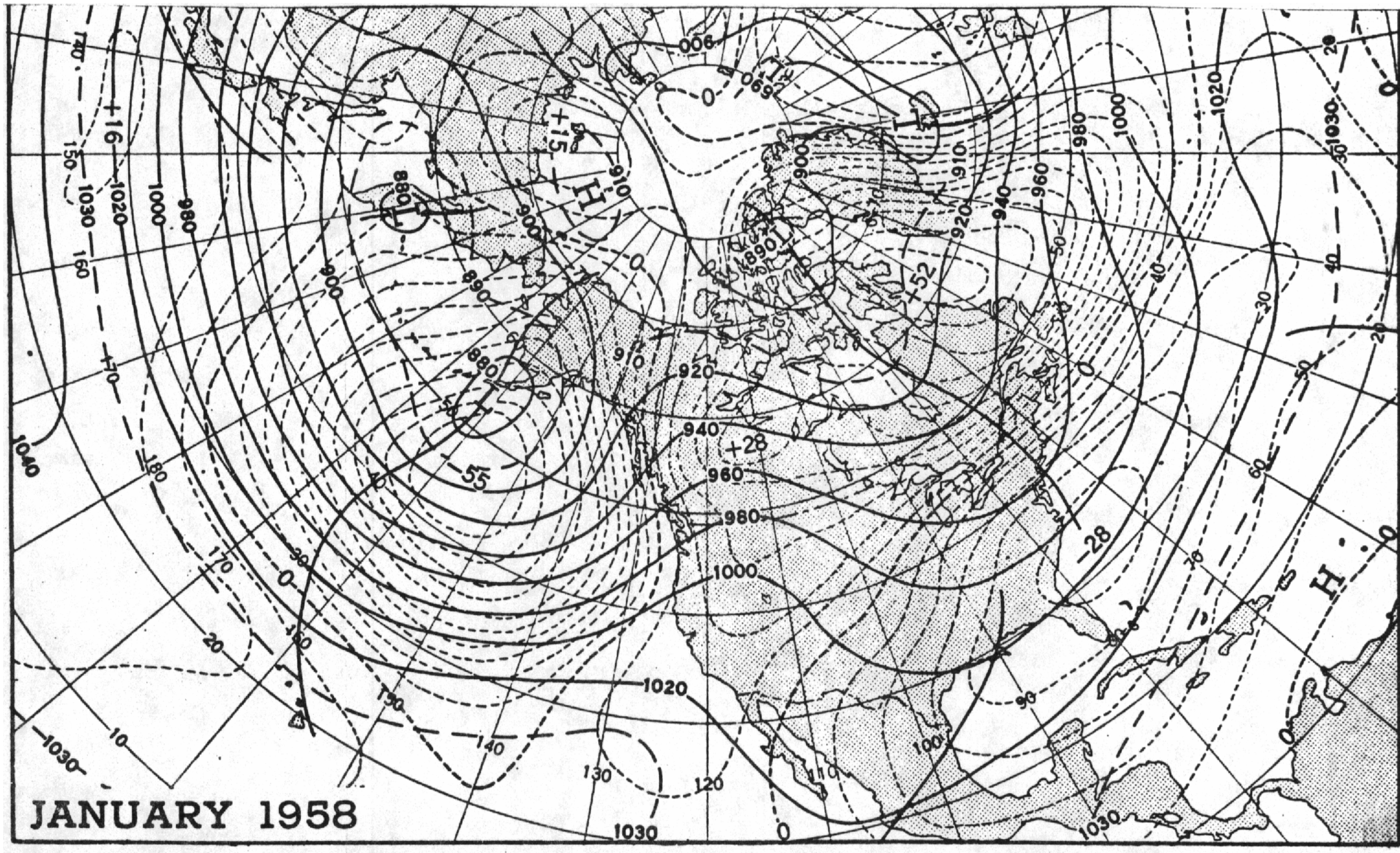
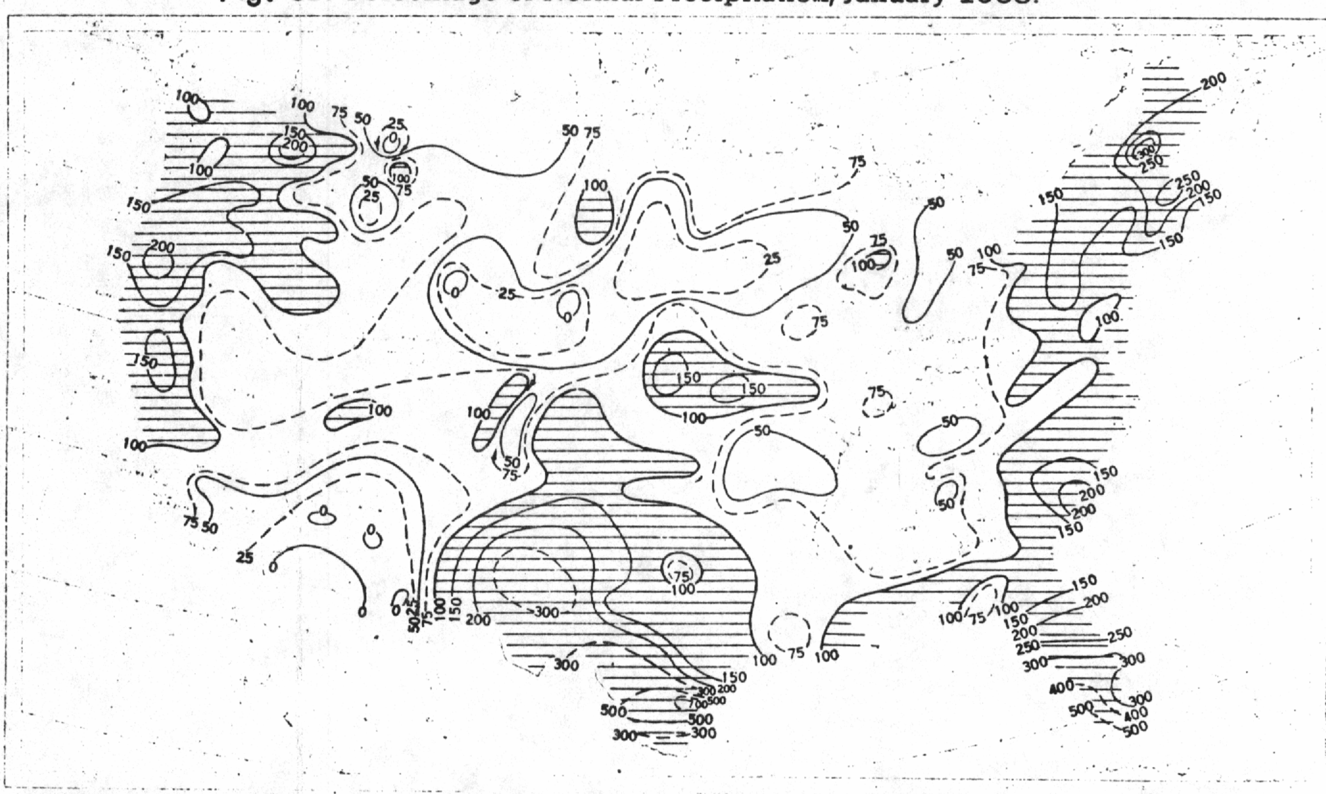


FIGURE 6a.-Monthly mean 700-mb. contours for January 1958 labeled in tens of feet, and height departures from normal (short dashed lines at 50-ft. intervals, with centers labeled in tens of feet and zero isopleth heavier). Trough lines (heavier solid lines) connect minimum latitudes of contours.

Fig. 6B. Percentage of Normal Precipitation, January 1958.



Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

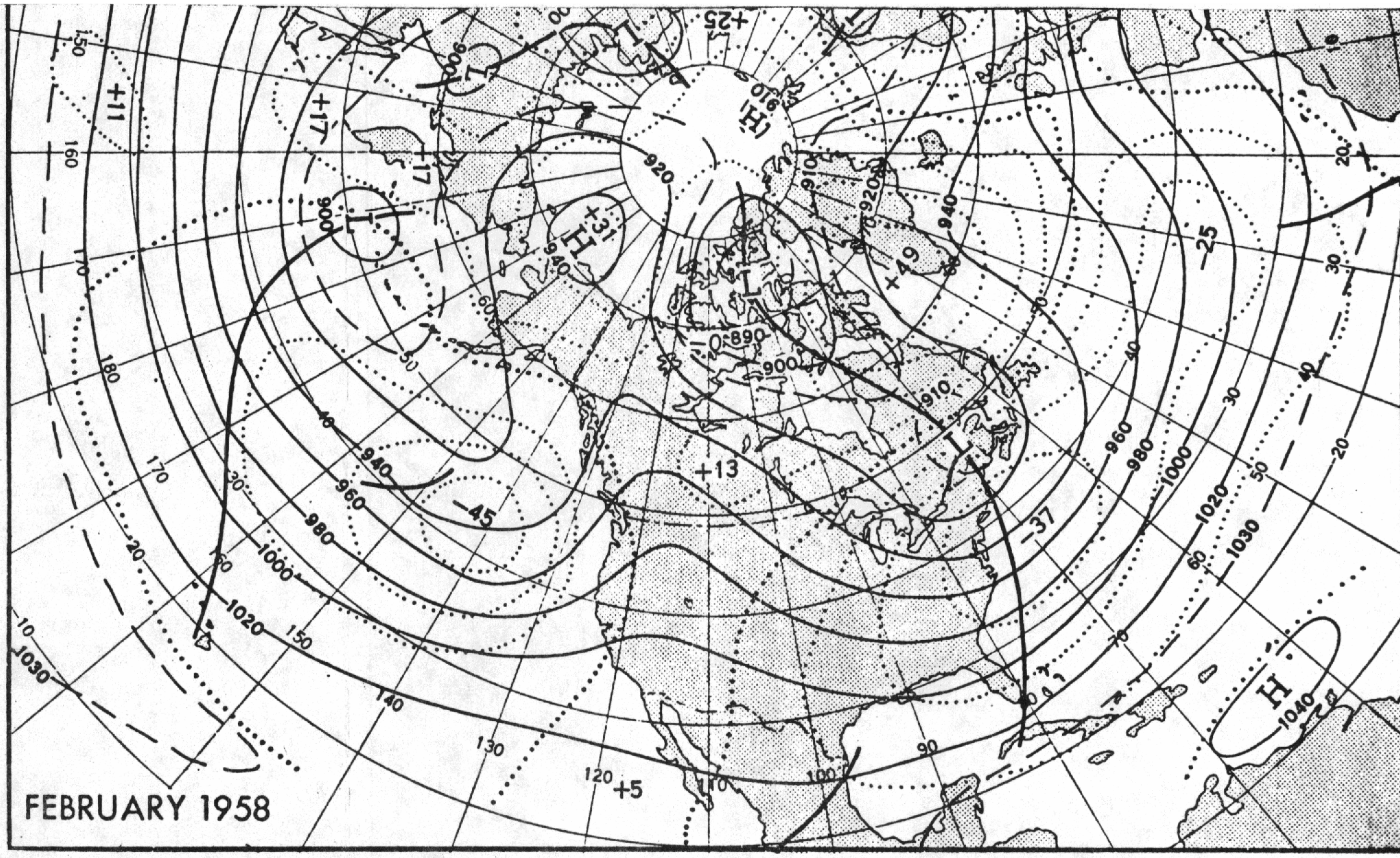
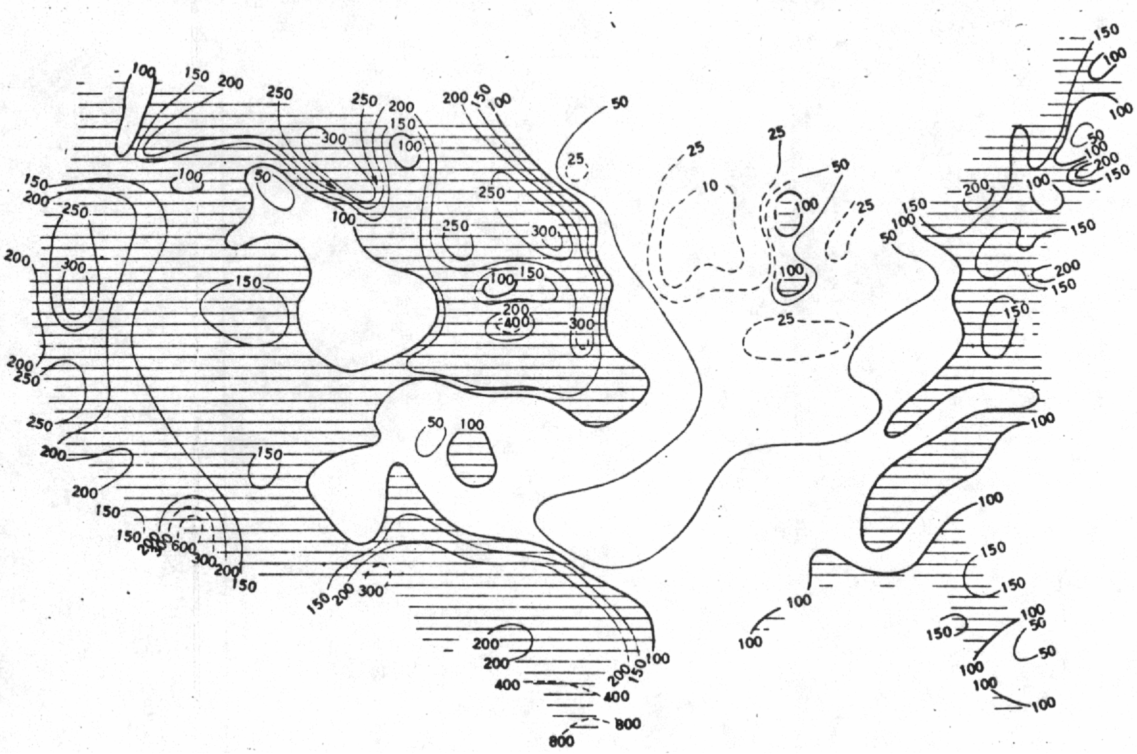


FIGURE 7a.–Mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for February 1958. Large, positive anomalies in polar regions were accompanied by an almost circumpolar ring of negative anomalies to the south.

Fig. 7B. Percentage of Normal Precipitation, February 1958.



Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

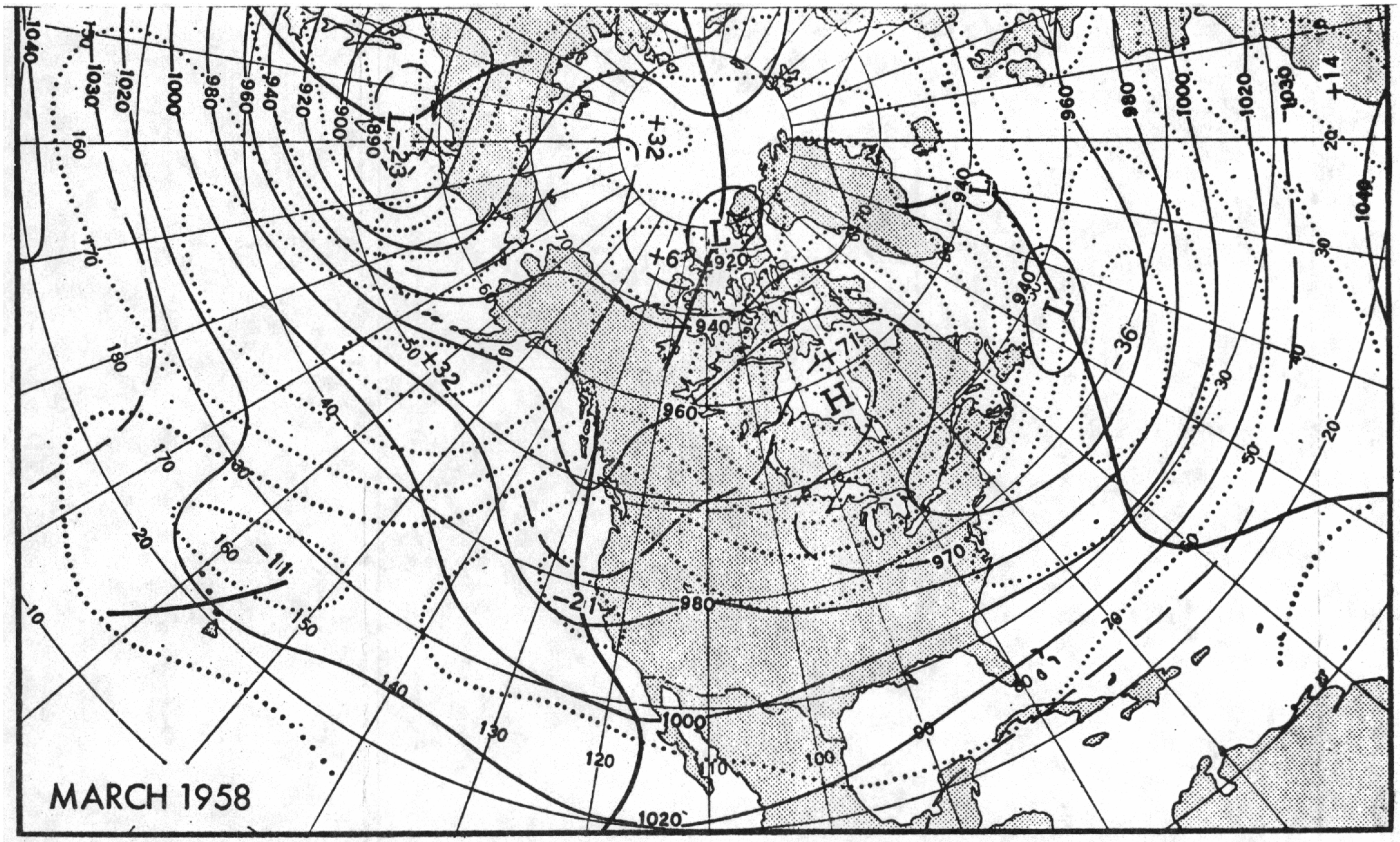
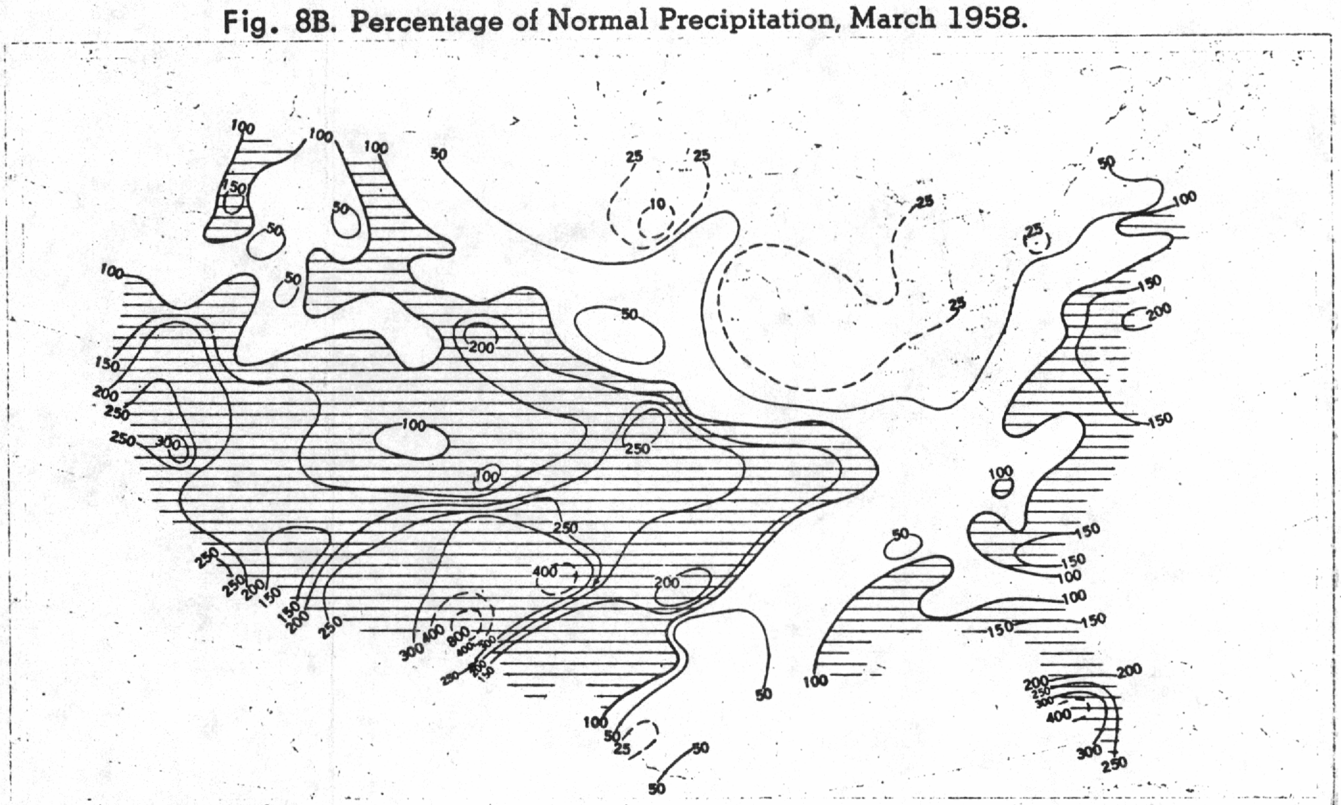


FIGURE 8a—Mean 700-mb. contours (solid) and height departures from normal (dotted), both in tens of feet, for March 1958. Note the large positive departures from normal from eastern Canada to the northeastern Pacific and across Greenland to the Polar Basin.

Fig. 8B. Percentage of Normal Precipitation, March 1958.



Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

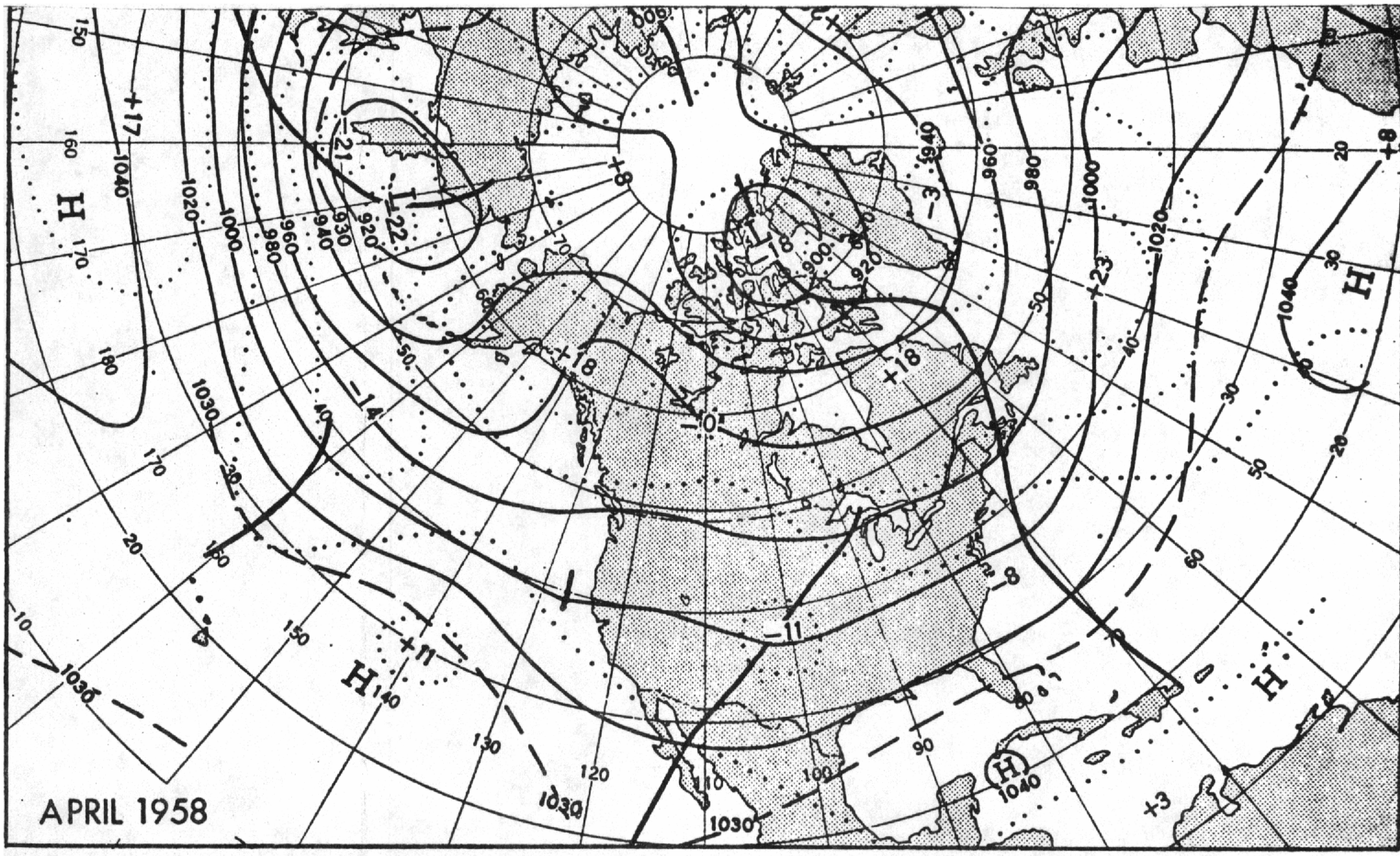
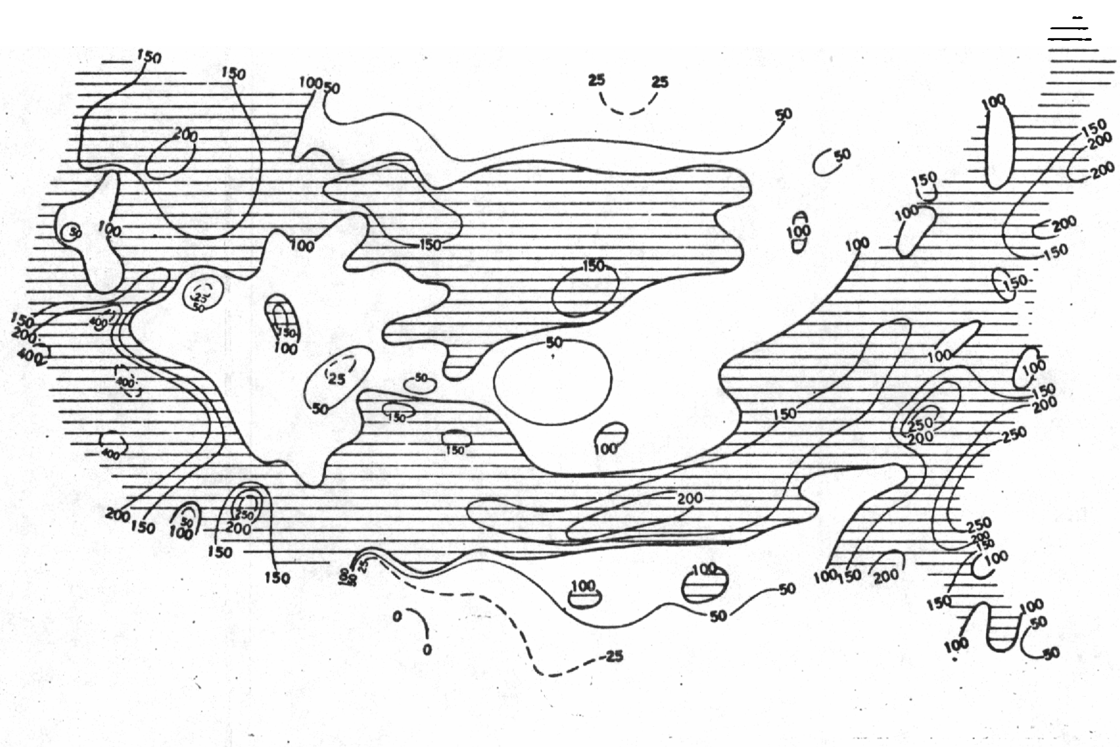


FIGURE 9a—Mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for April 1958. High-latitude blocking over North America is defined by the positive height departures in the north and negative height departures to the south.

Fig. 9B. Percentage of Normal Precipitation, April 1958.



Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

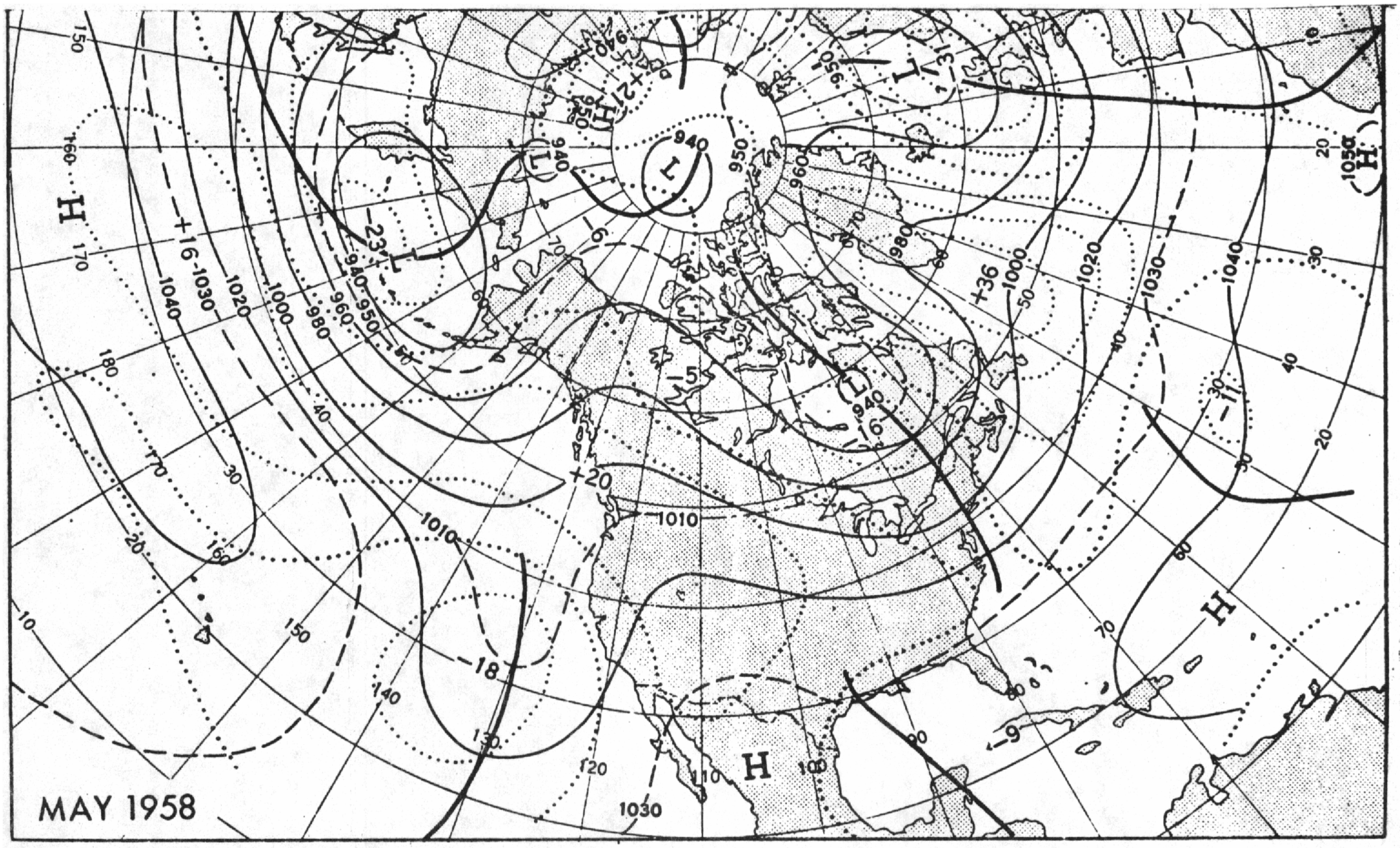
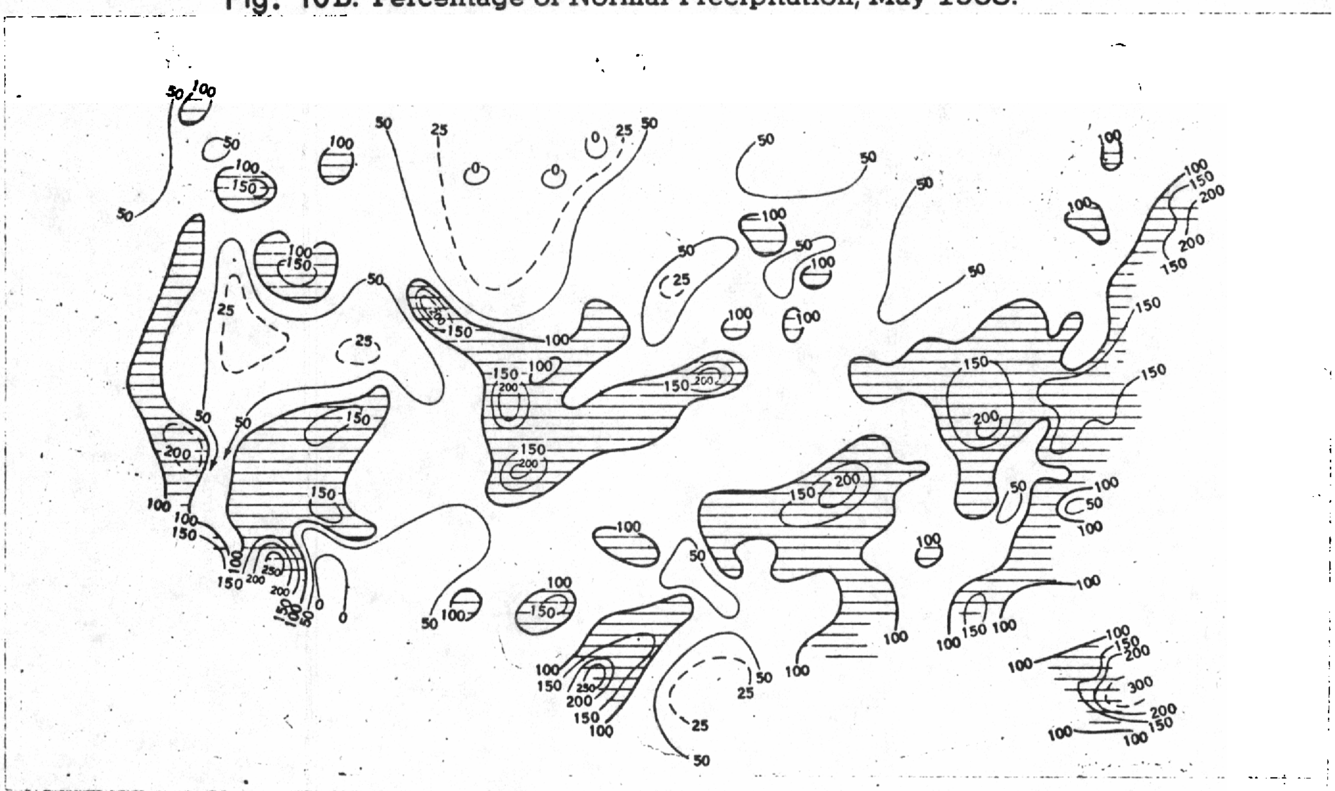


FIGURE 10a.-Mean 700-mb. height contours (solid) and departure from normal (dotted) (both in tens of feet) for May 1958. **Principal** circulation features in North America were stronger than normal ridge in the West and deeper than normal trough in the **East.**

Fig. 10B. Percentage of Normal Precipitation, May 1958.



Normal monthly precipitation amounts are computed from the records for 1921-50 for Weather Bureau stations and from records of 25 years or more (mostly 1931-55) for cooperative stations.

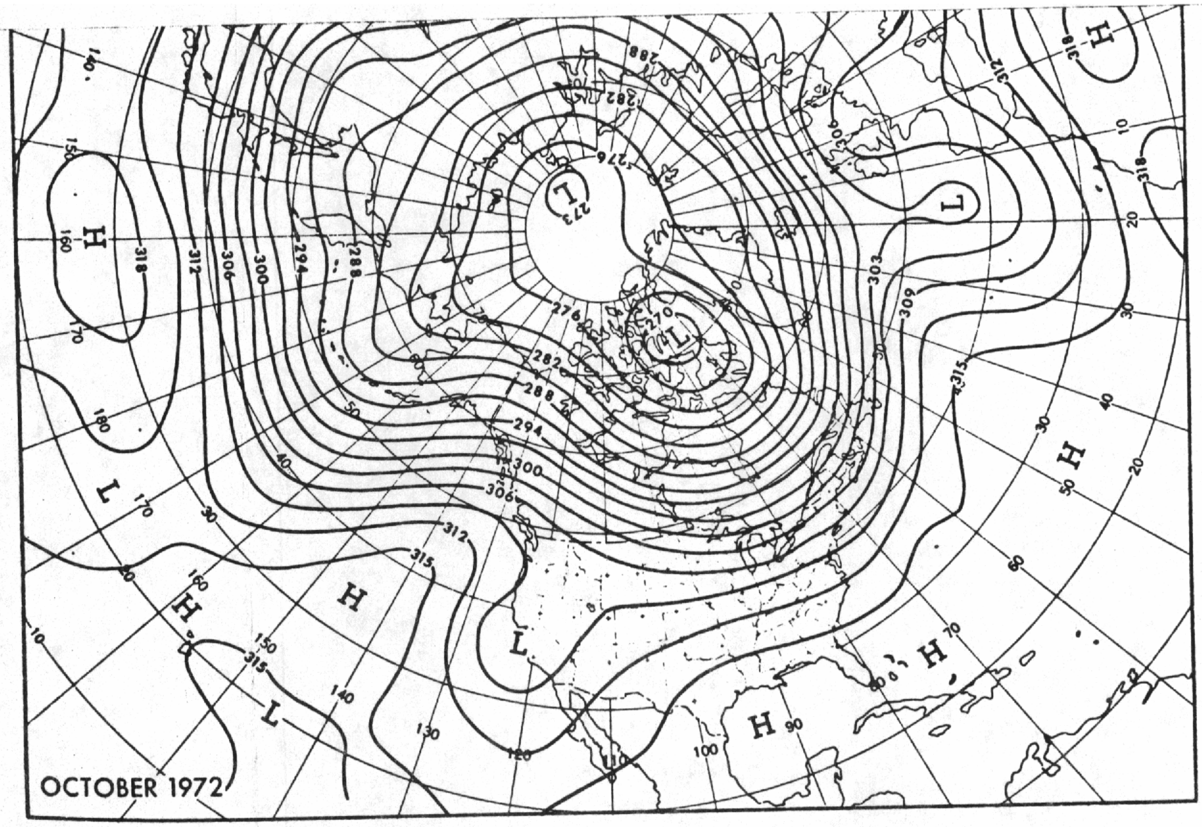
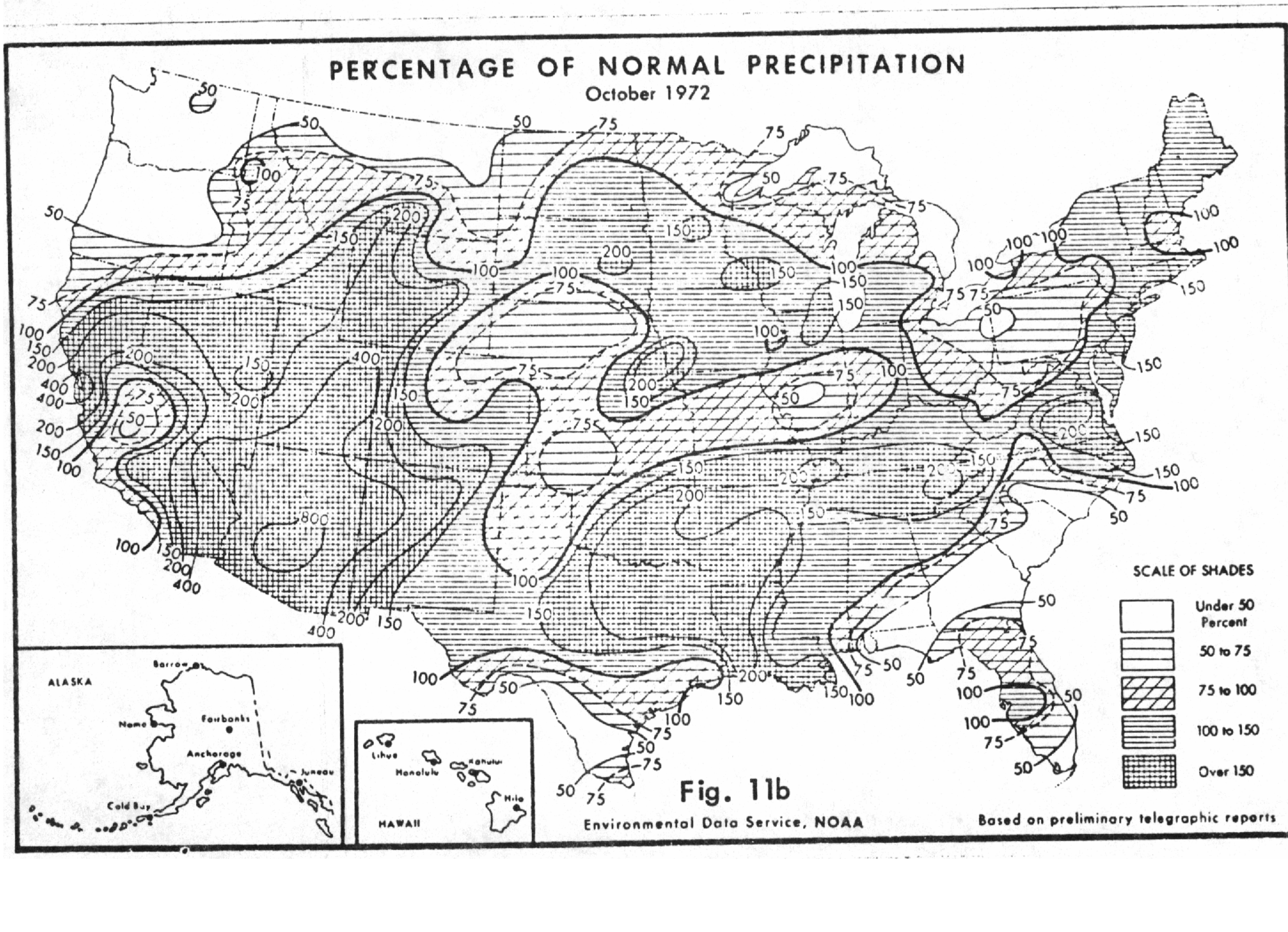


Figure 11a.—Mean 700-mb contours in dekameters (dam) for October 1972.



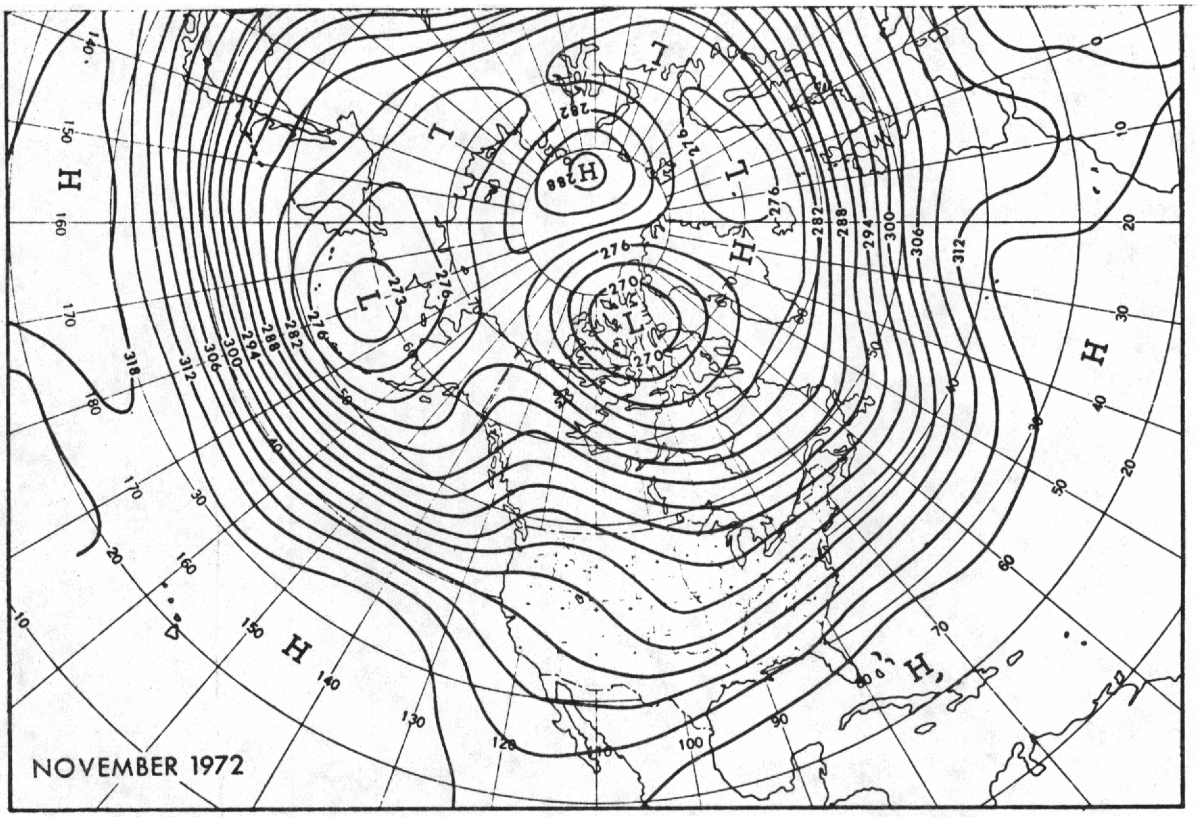
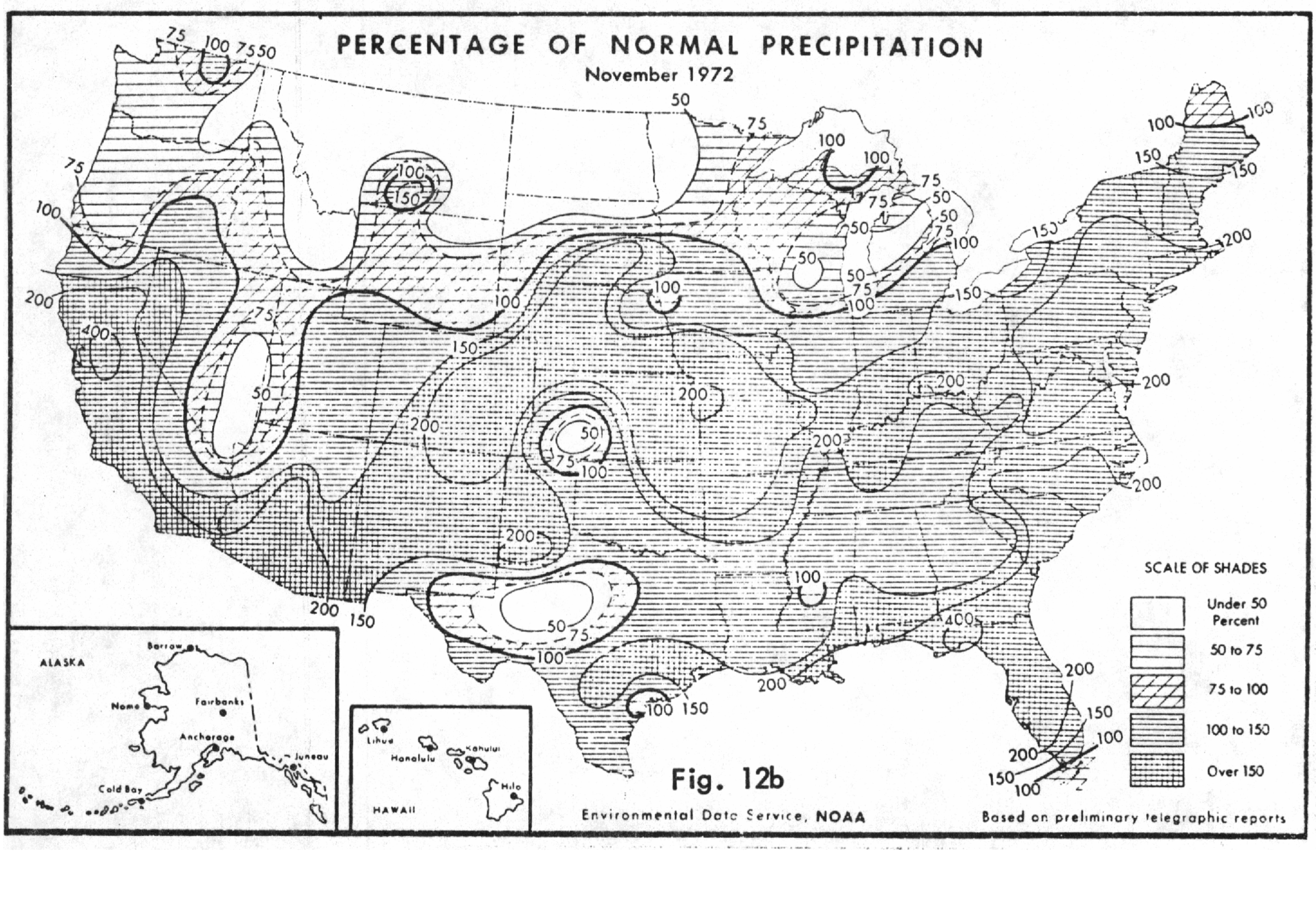


FIGURE 12a–Mean 700-mb contours in dekameters (dam) for November 1972.



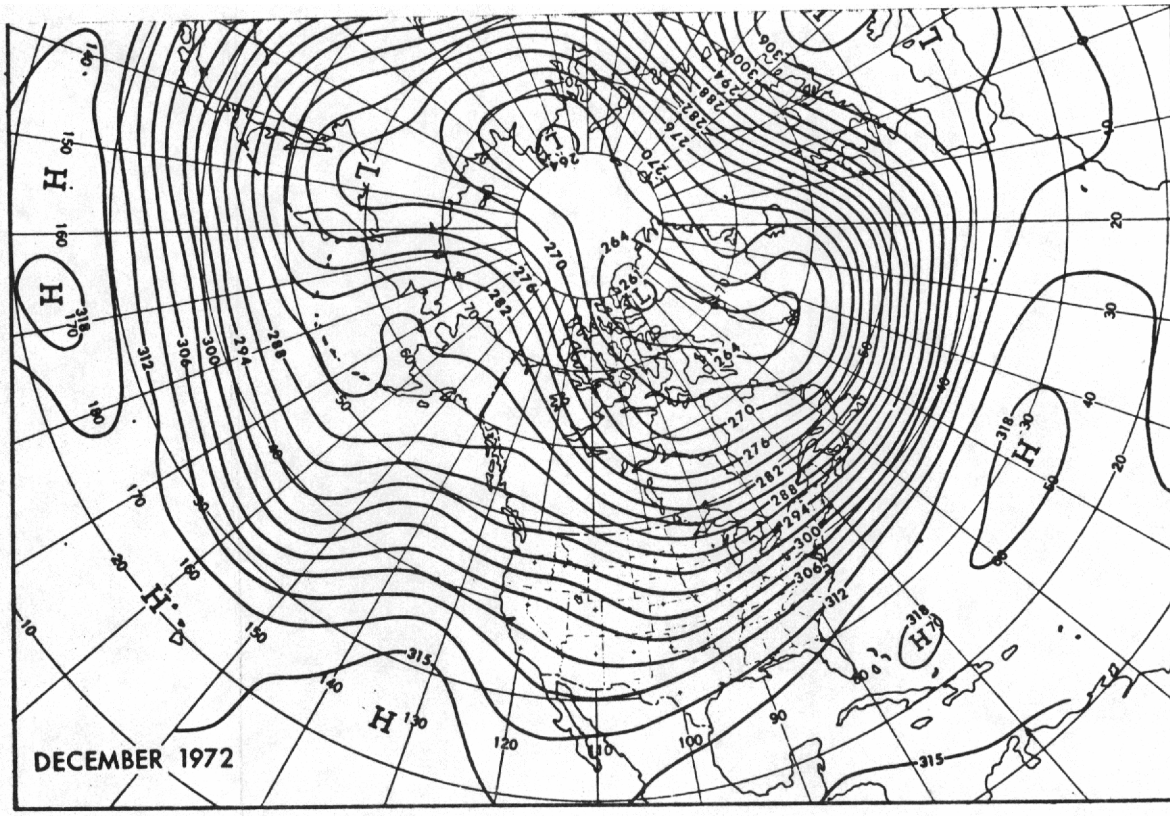


FIGURE 13a-Mean 700-mb contours in dekameters (dam) for December 1972

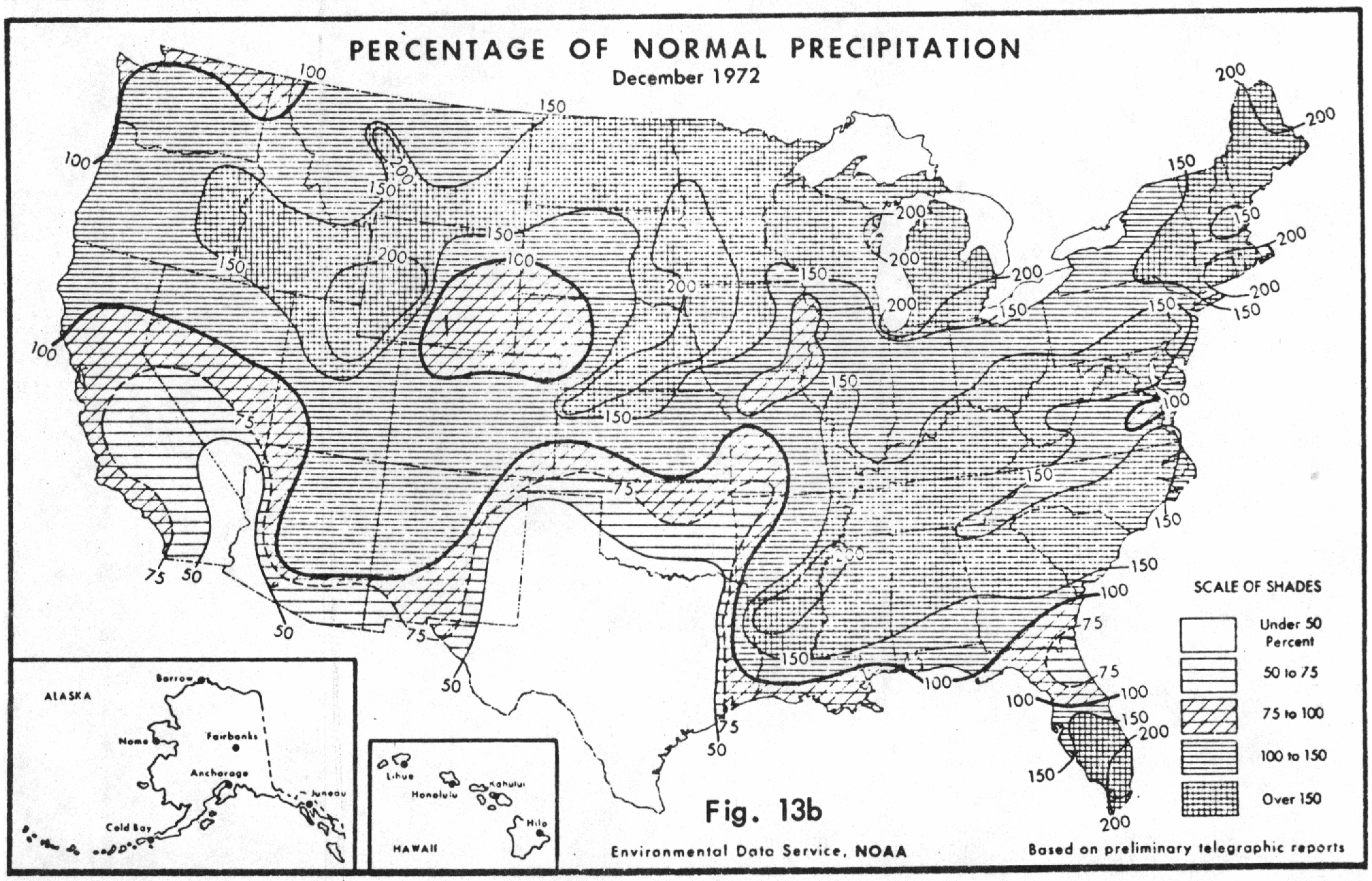


Fig. 13b

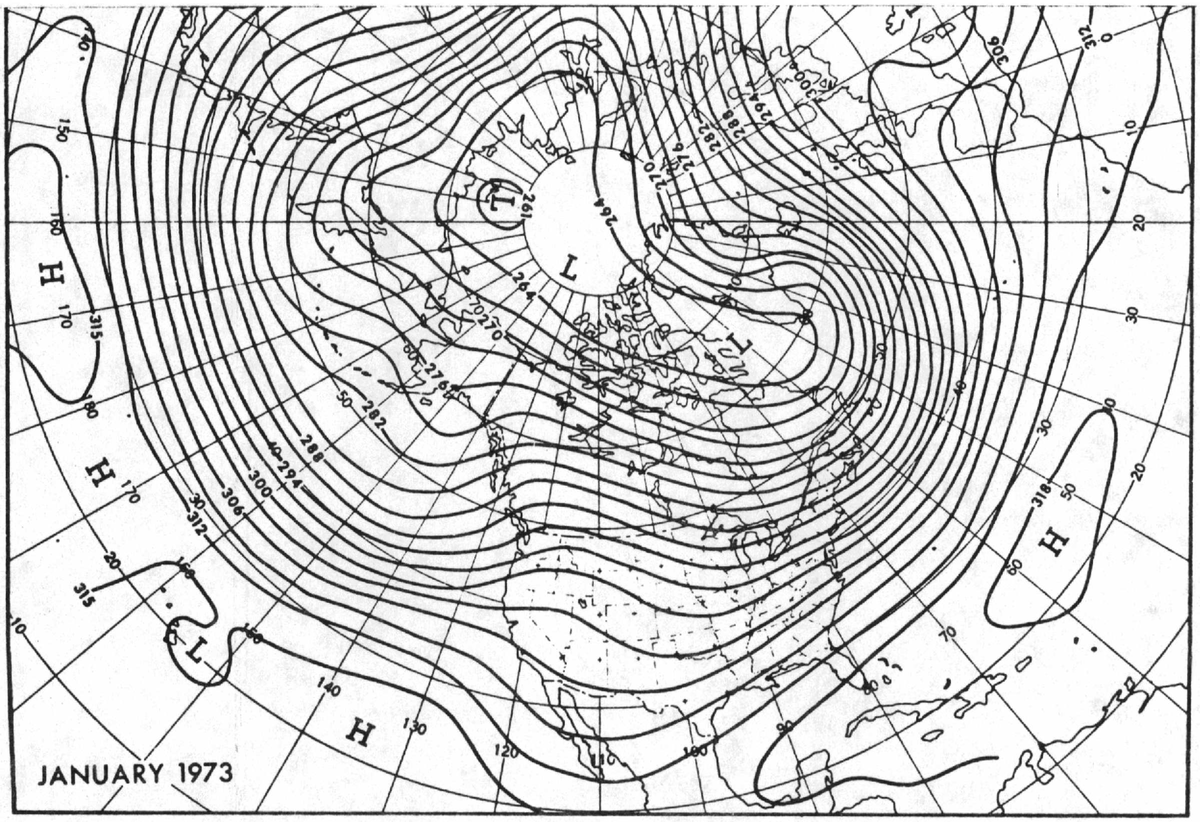
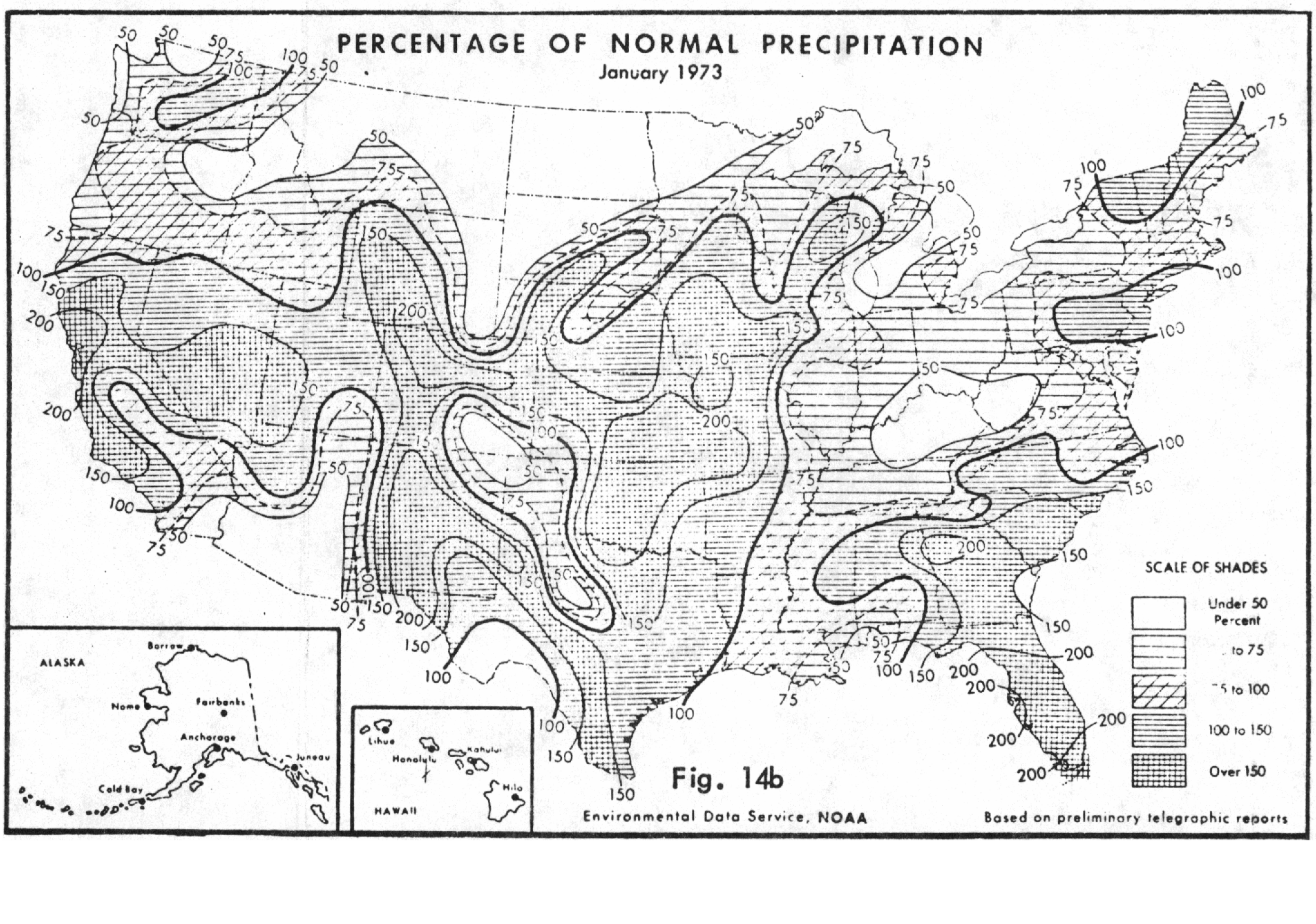


FIGURE 14a-Mean 700-mb contours in decameters (dam) for January 1973.



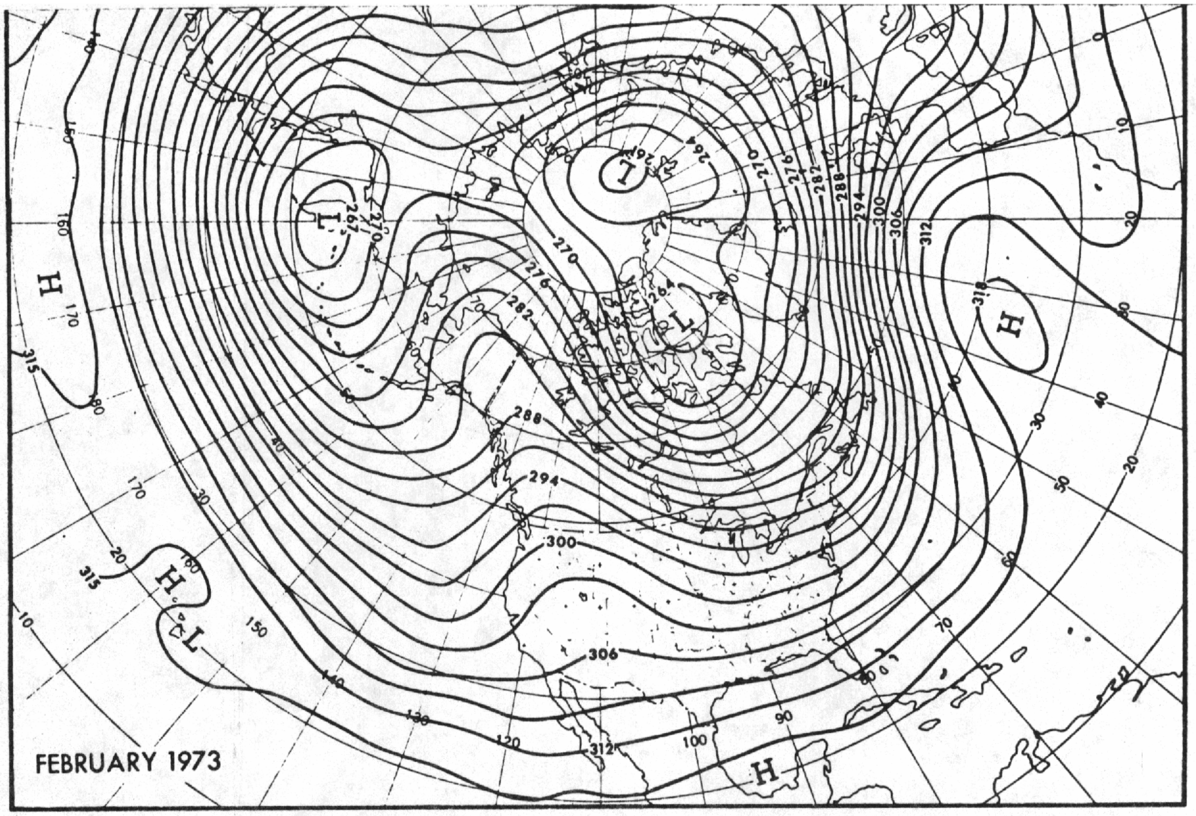


FIGURE 15a -Mean 700-mb contours in dekameters (dam) for February 1973.

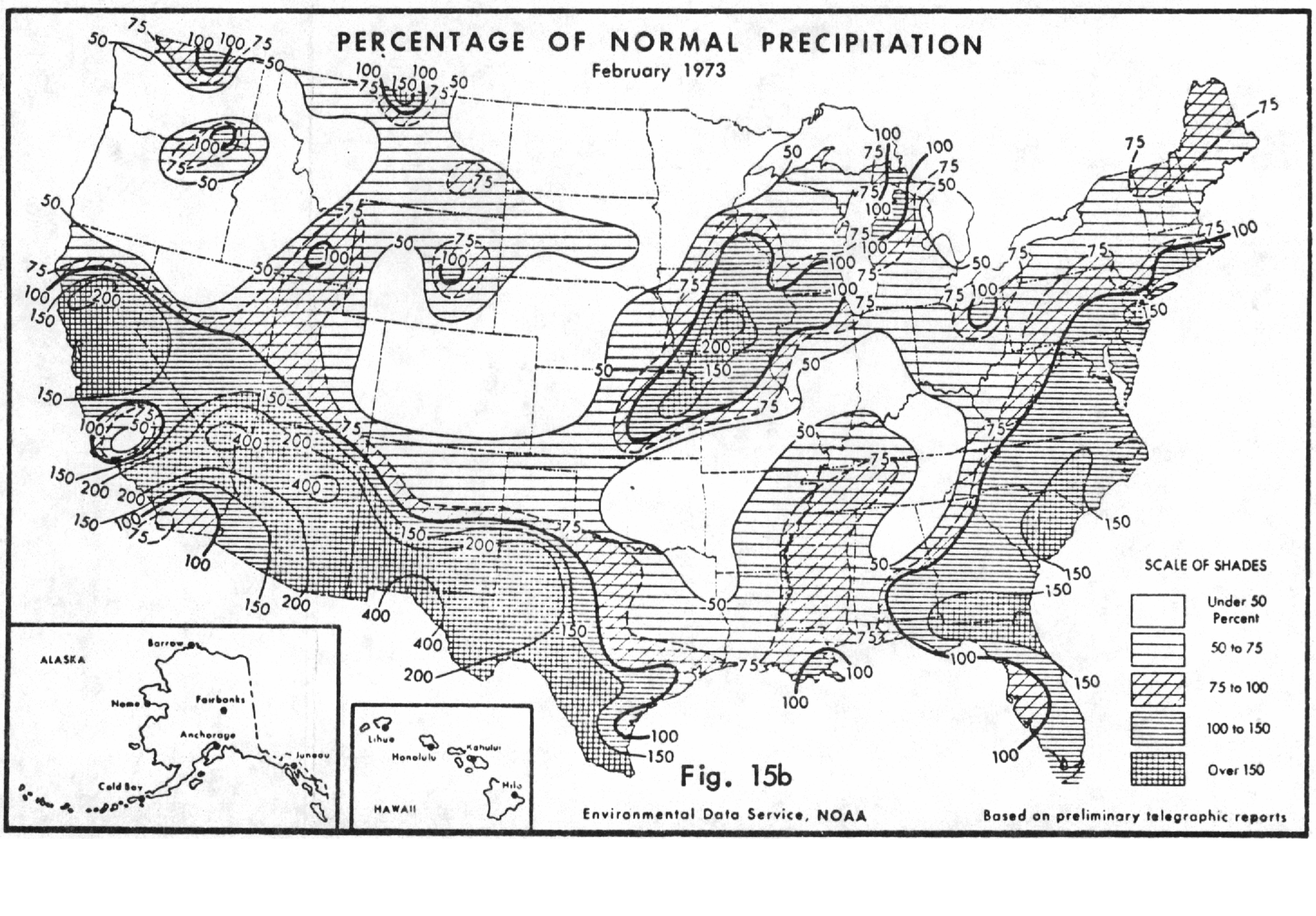


Fig. 15b

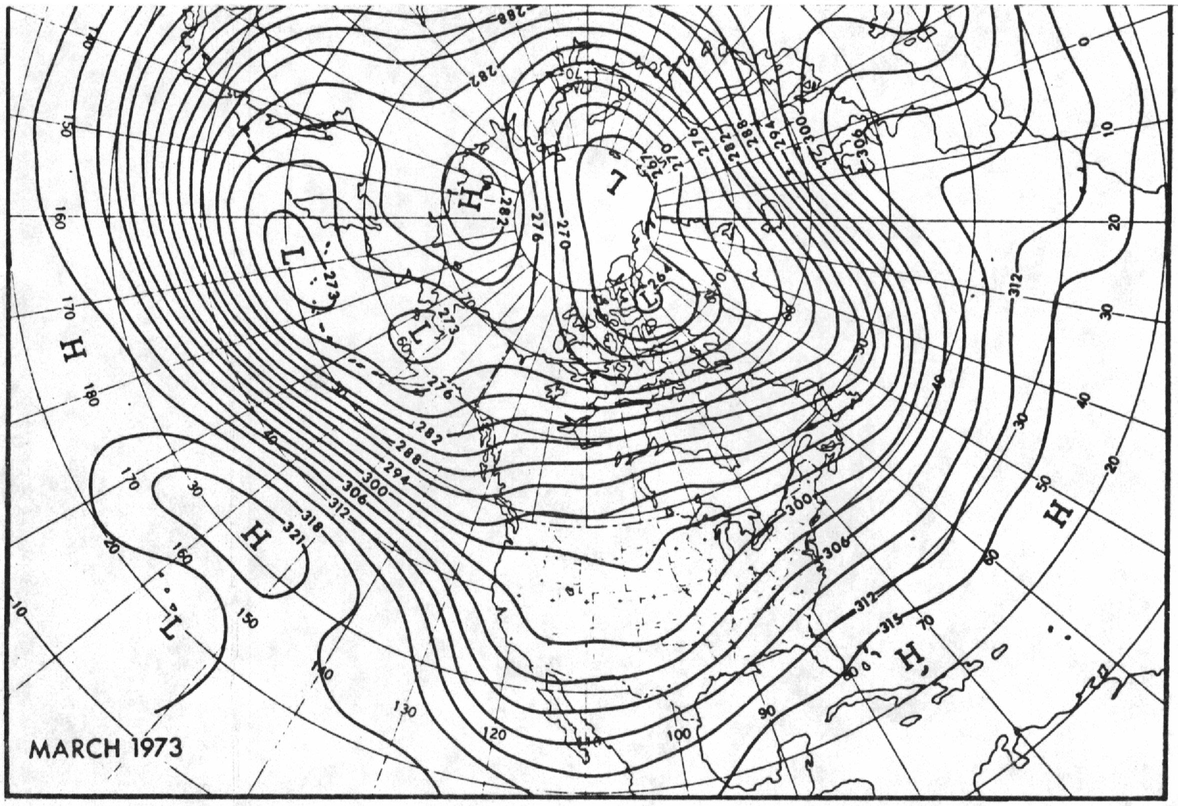


FIGURE 16a-Mean 700-mb contours in decameters (dam) for March 1973.

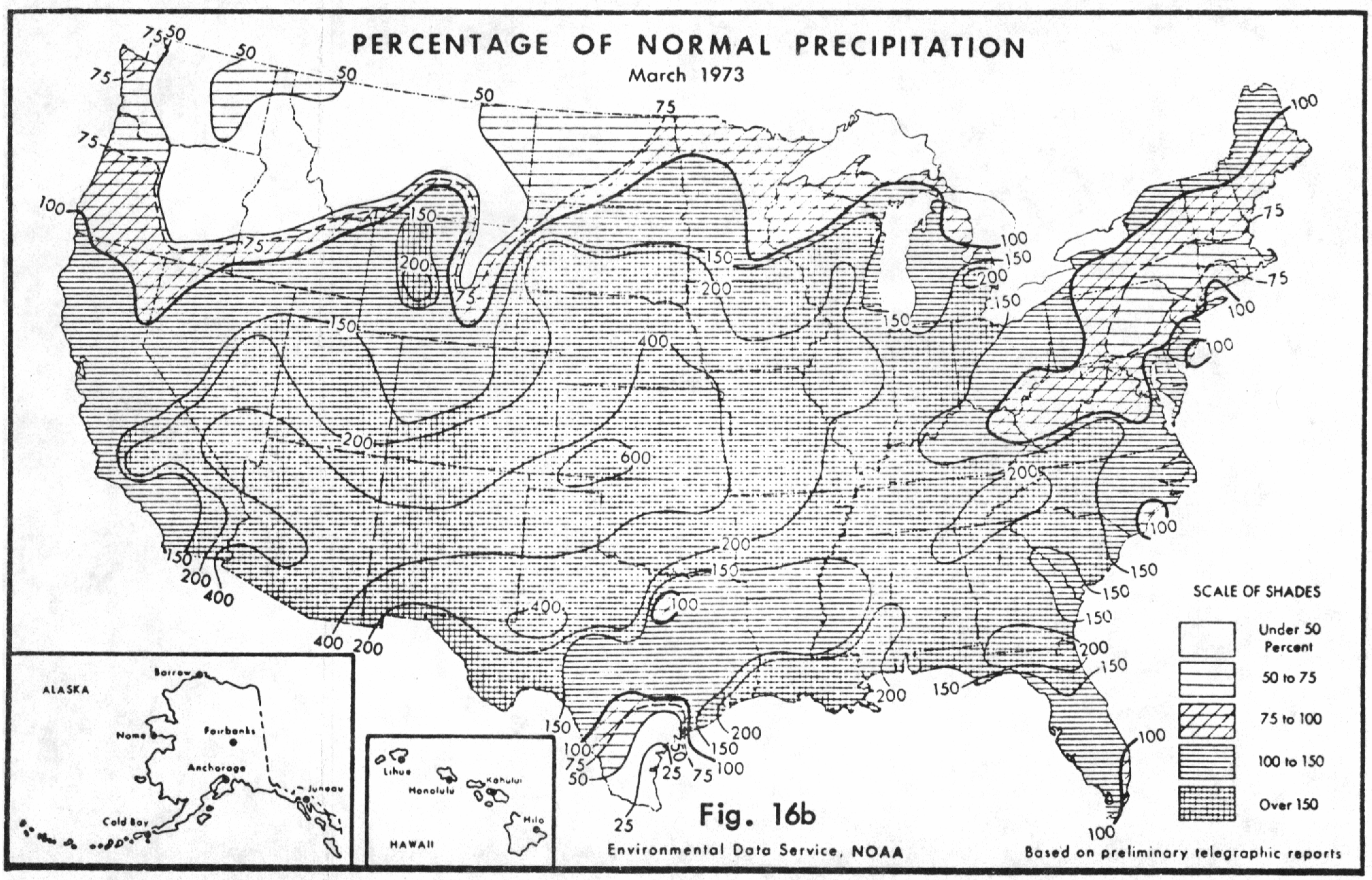


Fig. 16b

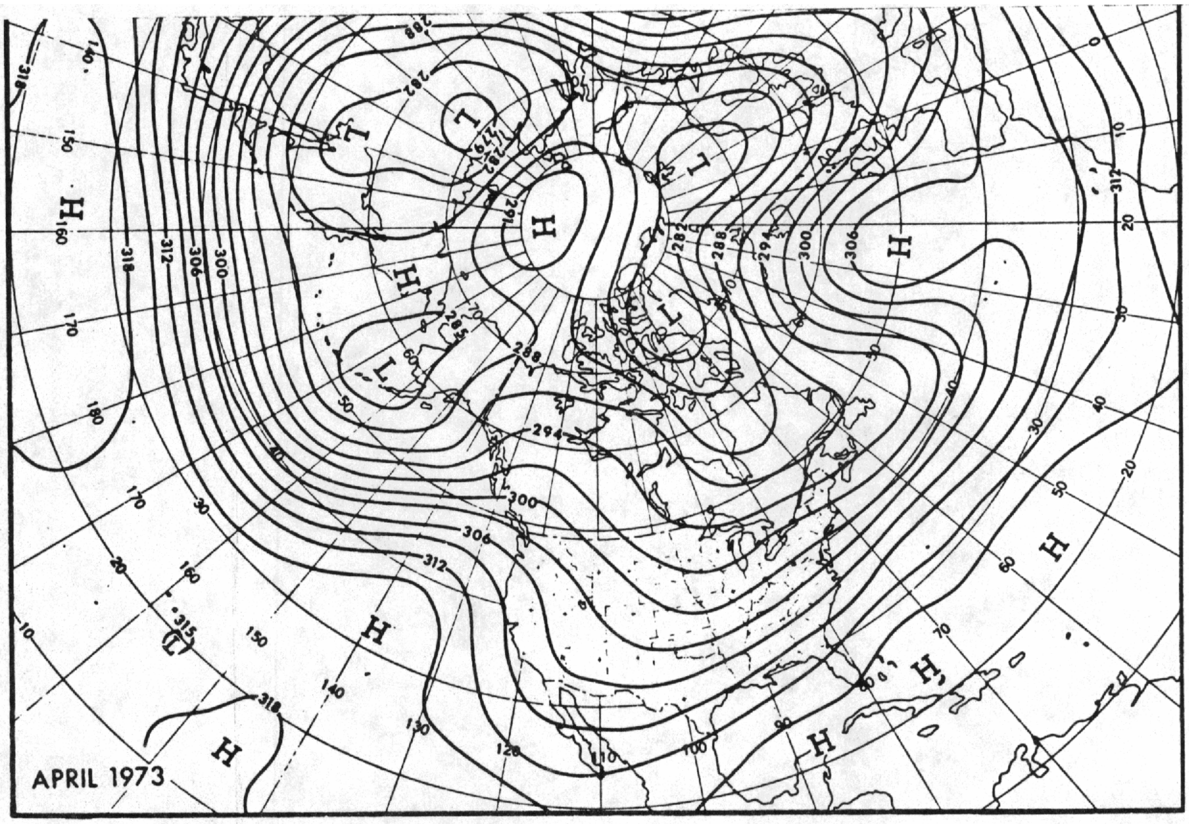
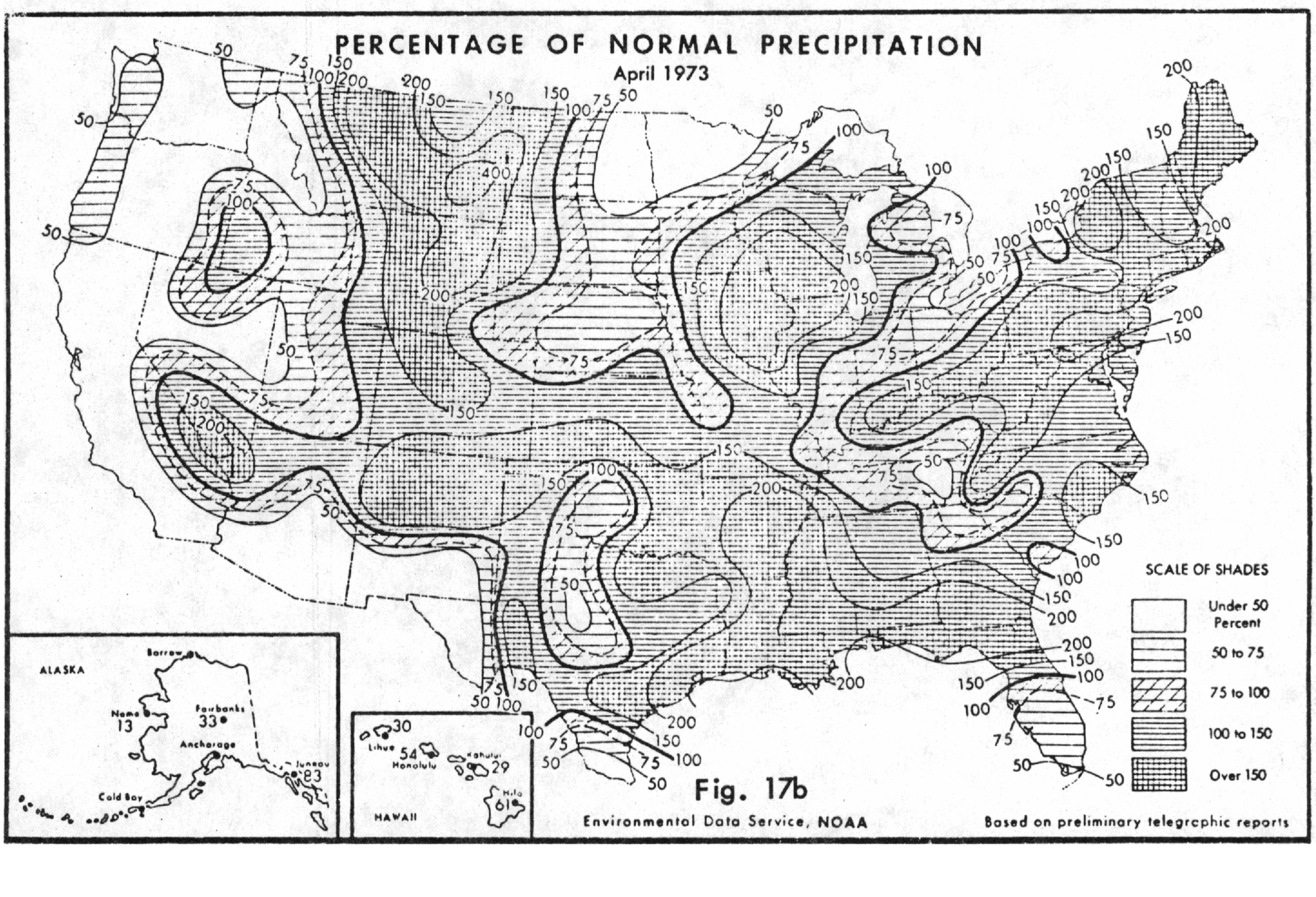


FIGURE 17a-Mean 700-mb height contours in dekameters (dam) for April 1973.



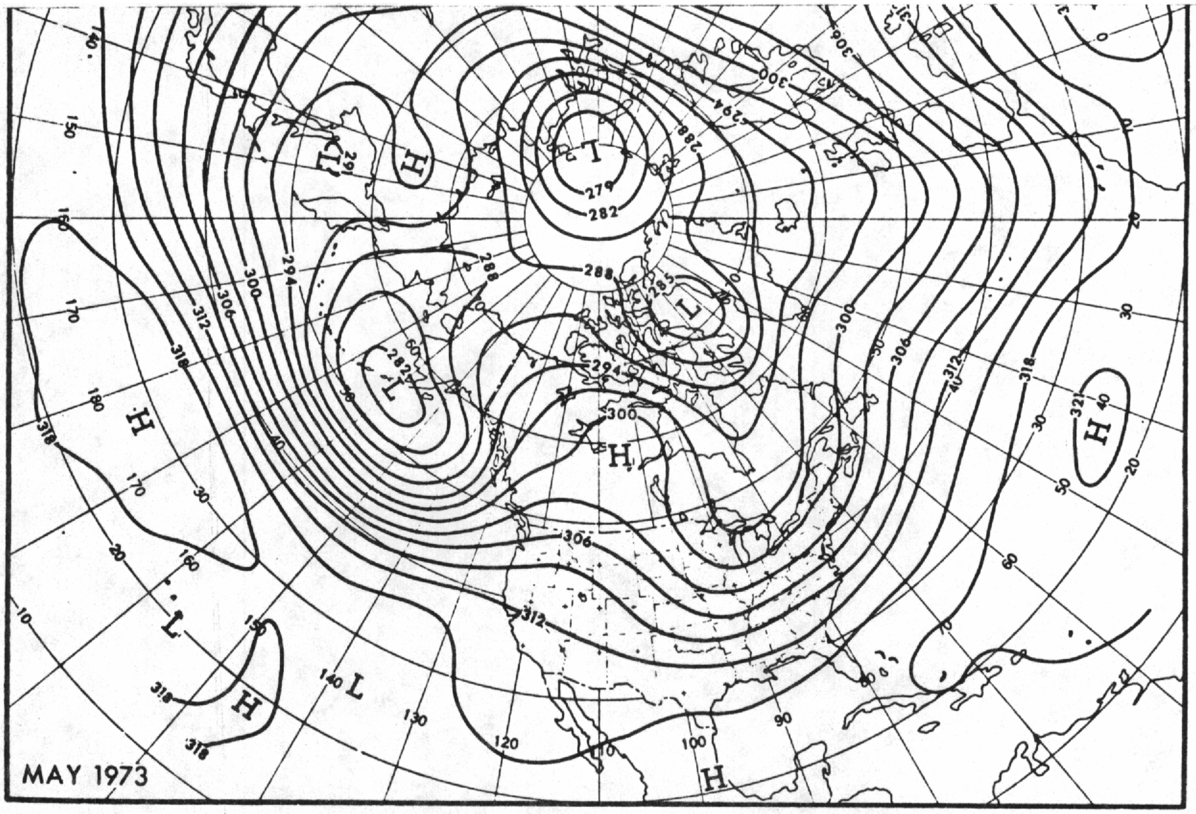
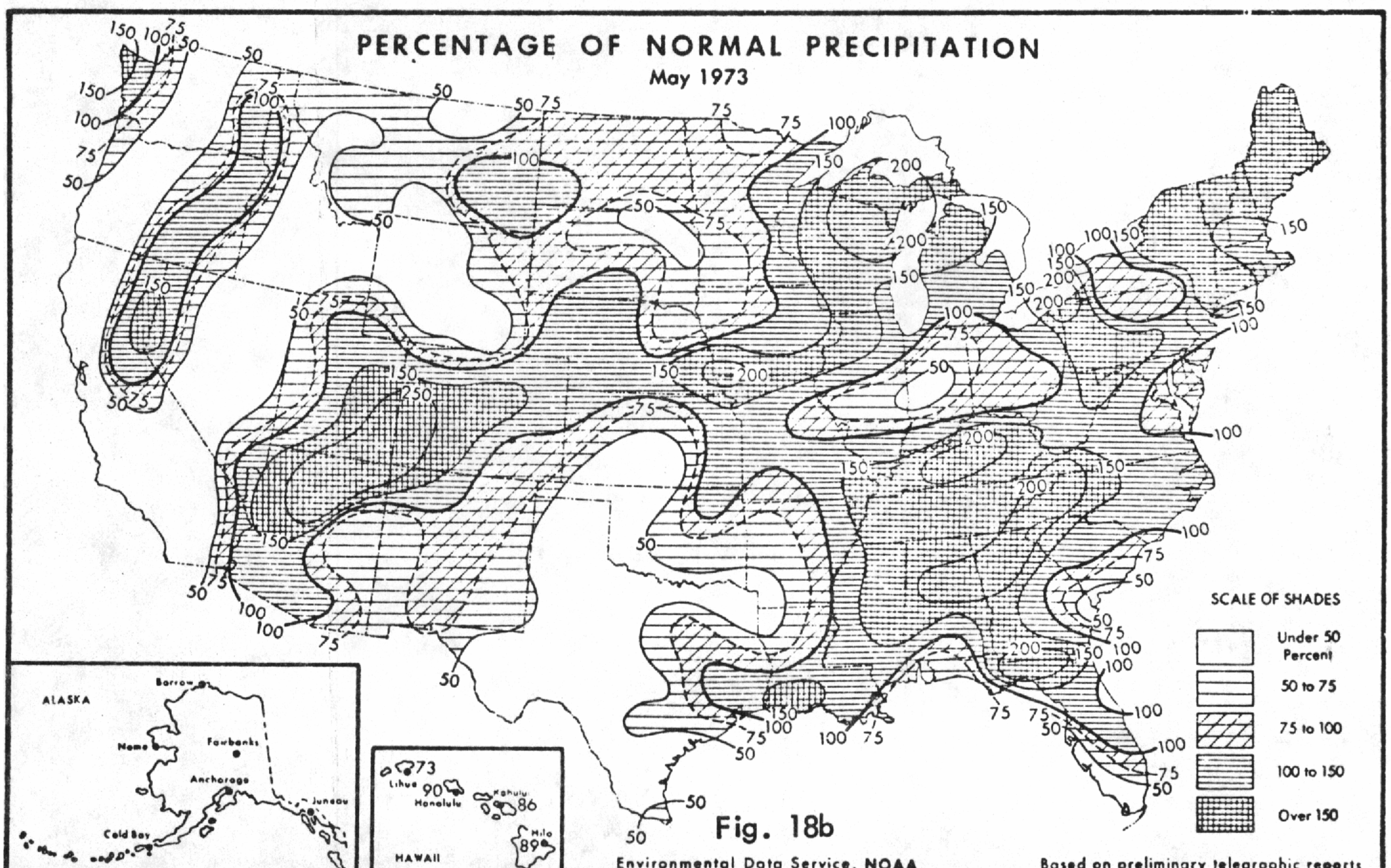


FIGURE 18a-Mean 700-mb height contours in dekameters (dam) for May 1973.



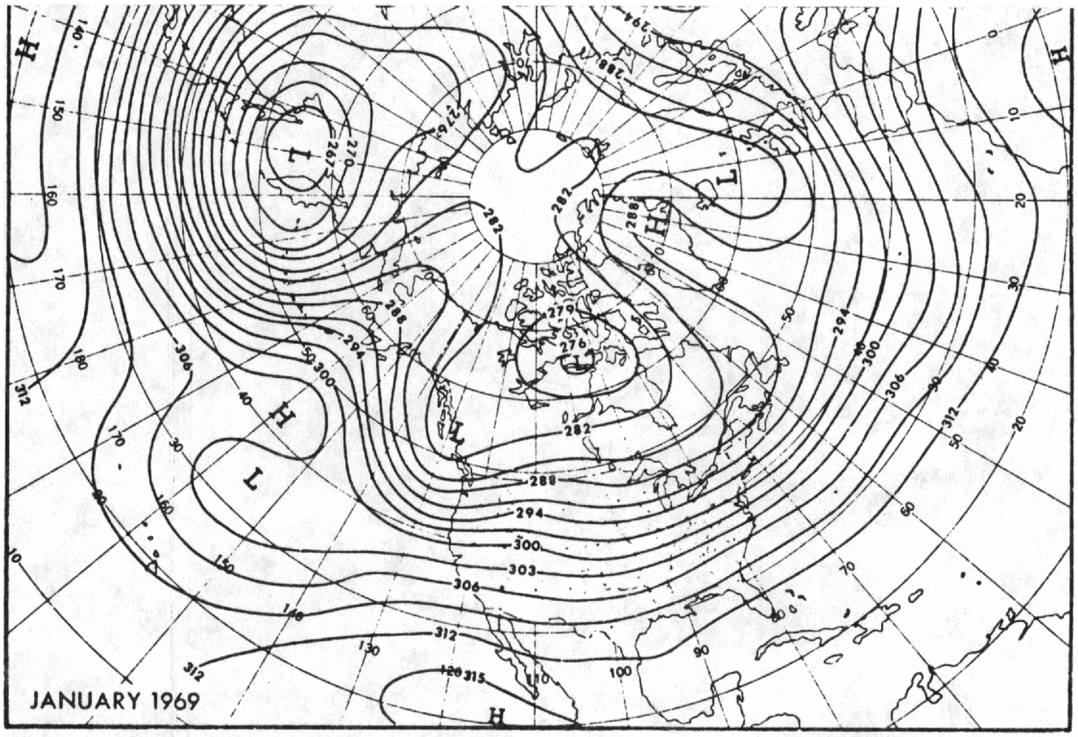
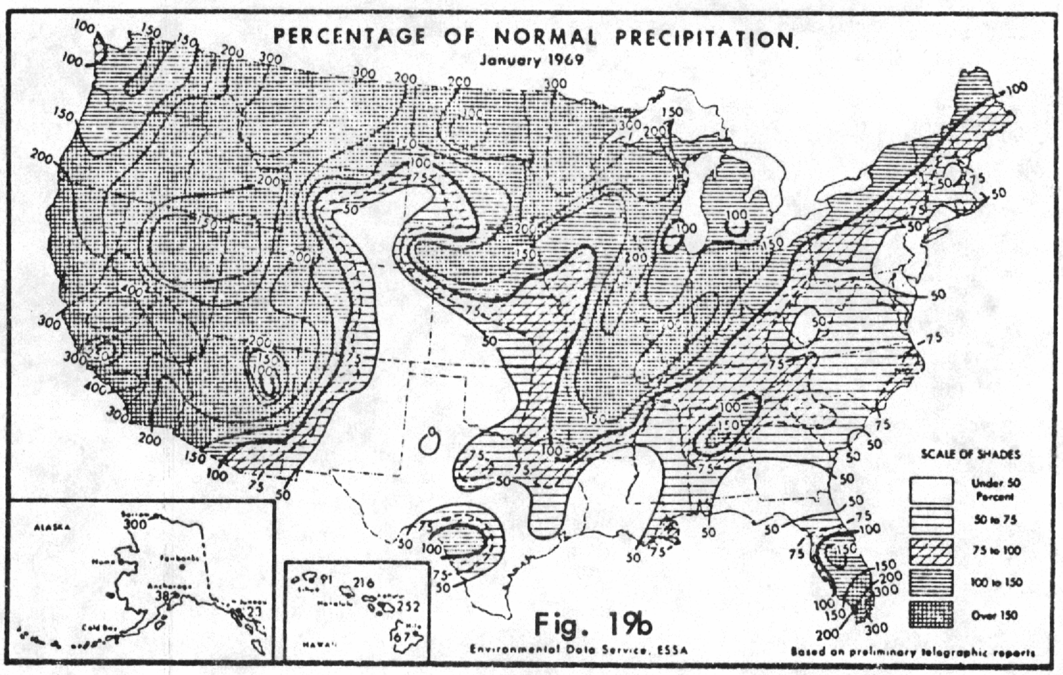


FIGURE 19a-Mean 700-mb contours (decameters) for January 1969.



Environmental Data Service, ESSA, charts.

Fig. 19c

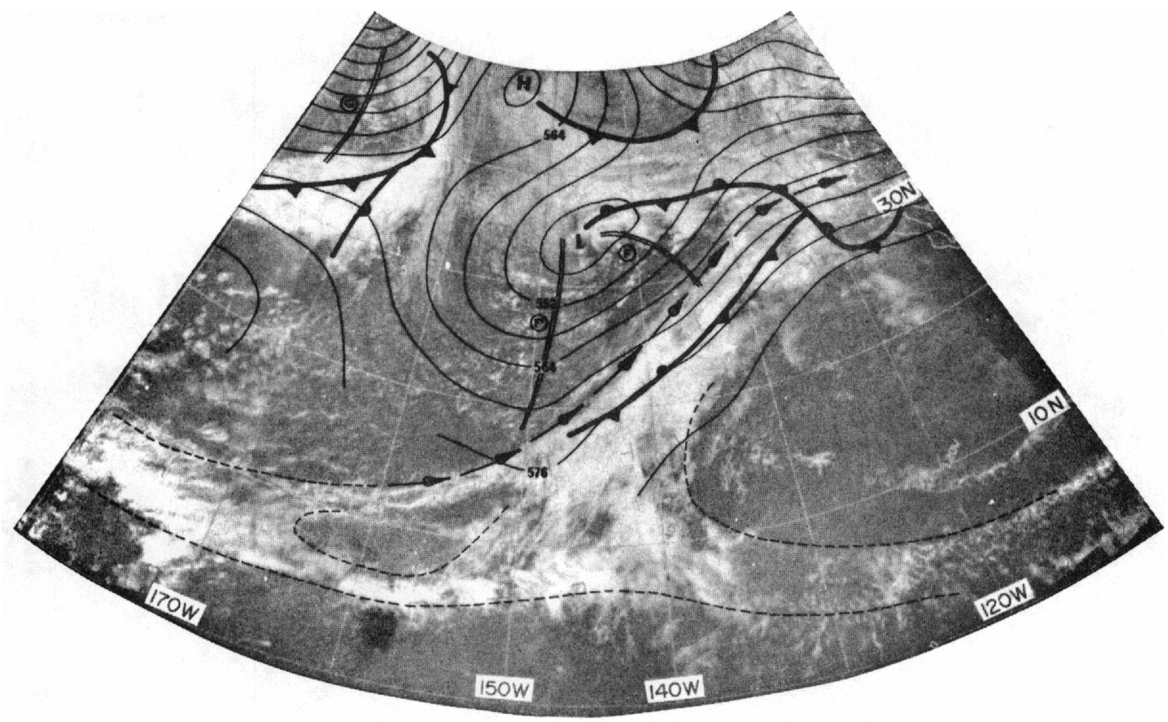


Fig. 19d

23 January 1969

Fig. 19e

Fig. 19f

24 January 1969

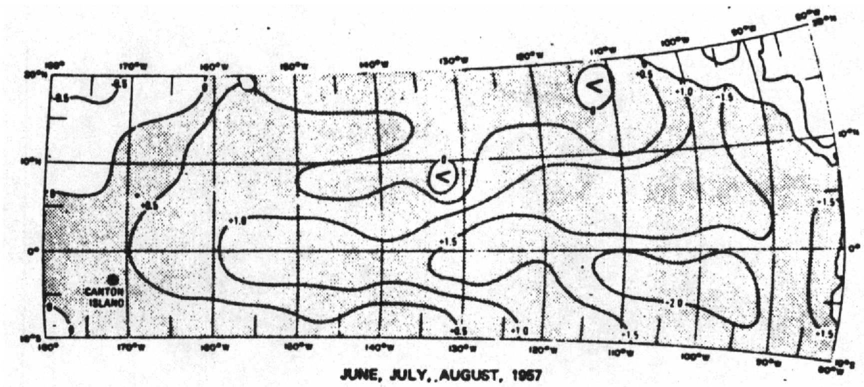


Fig. 20a

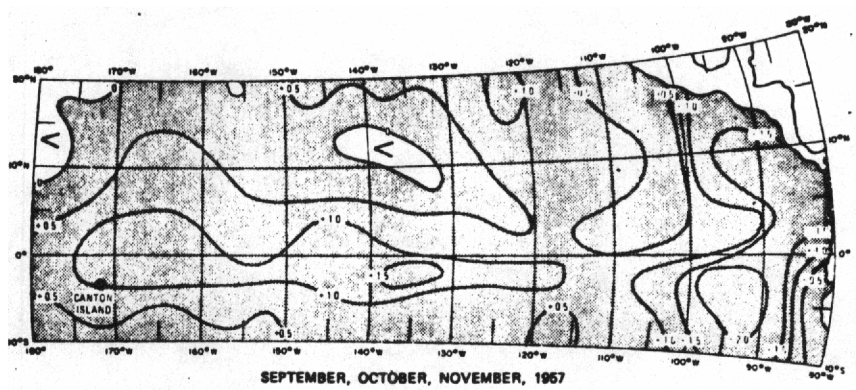


Fig. 20b

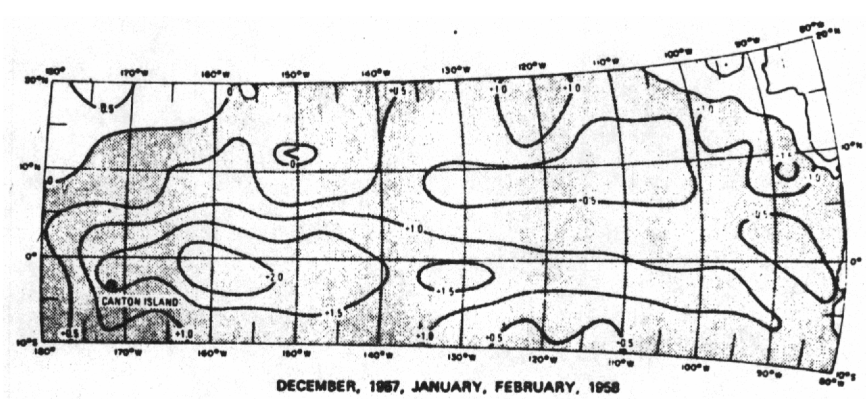


Fig. 20c

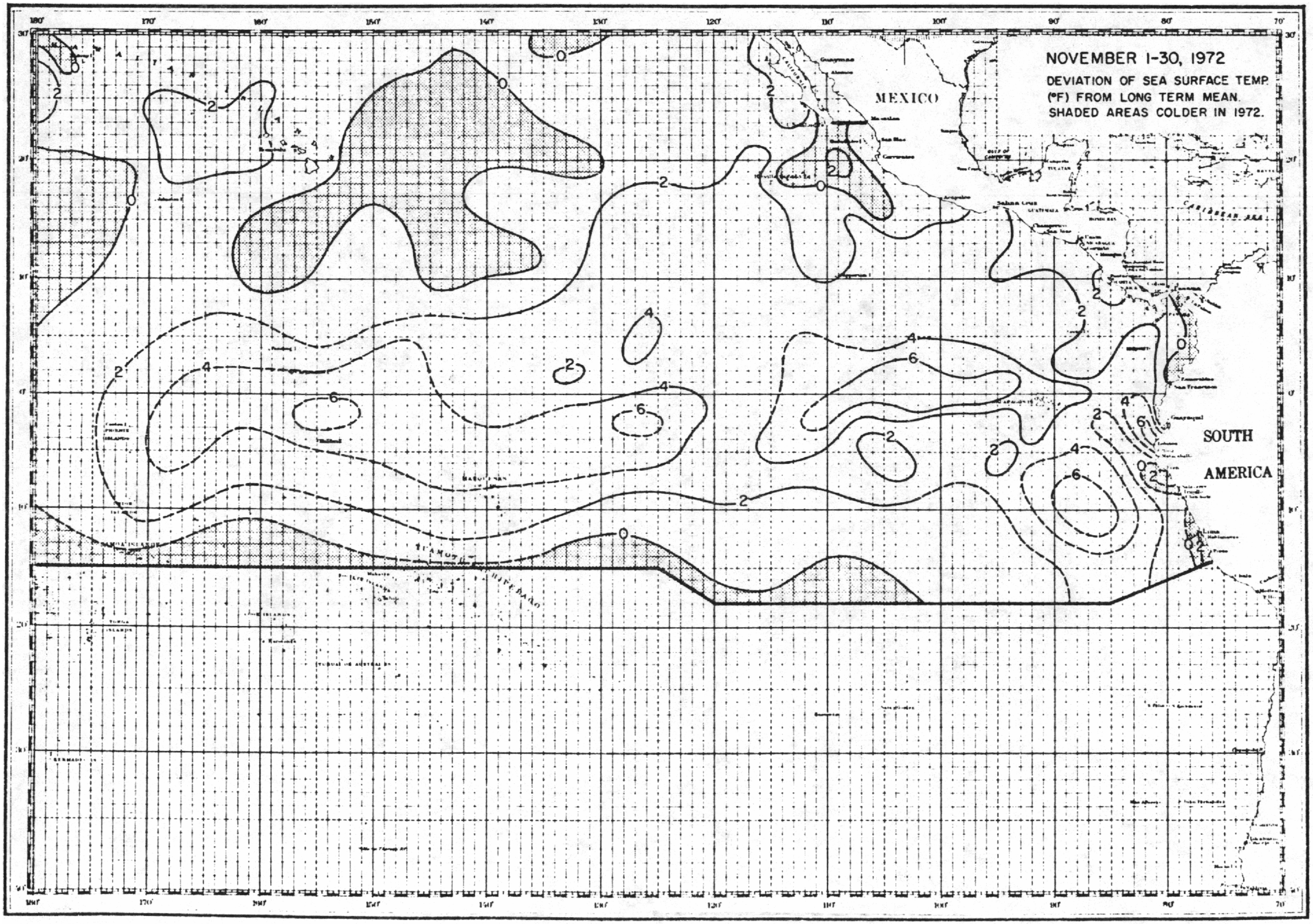
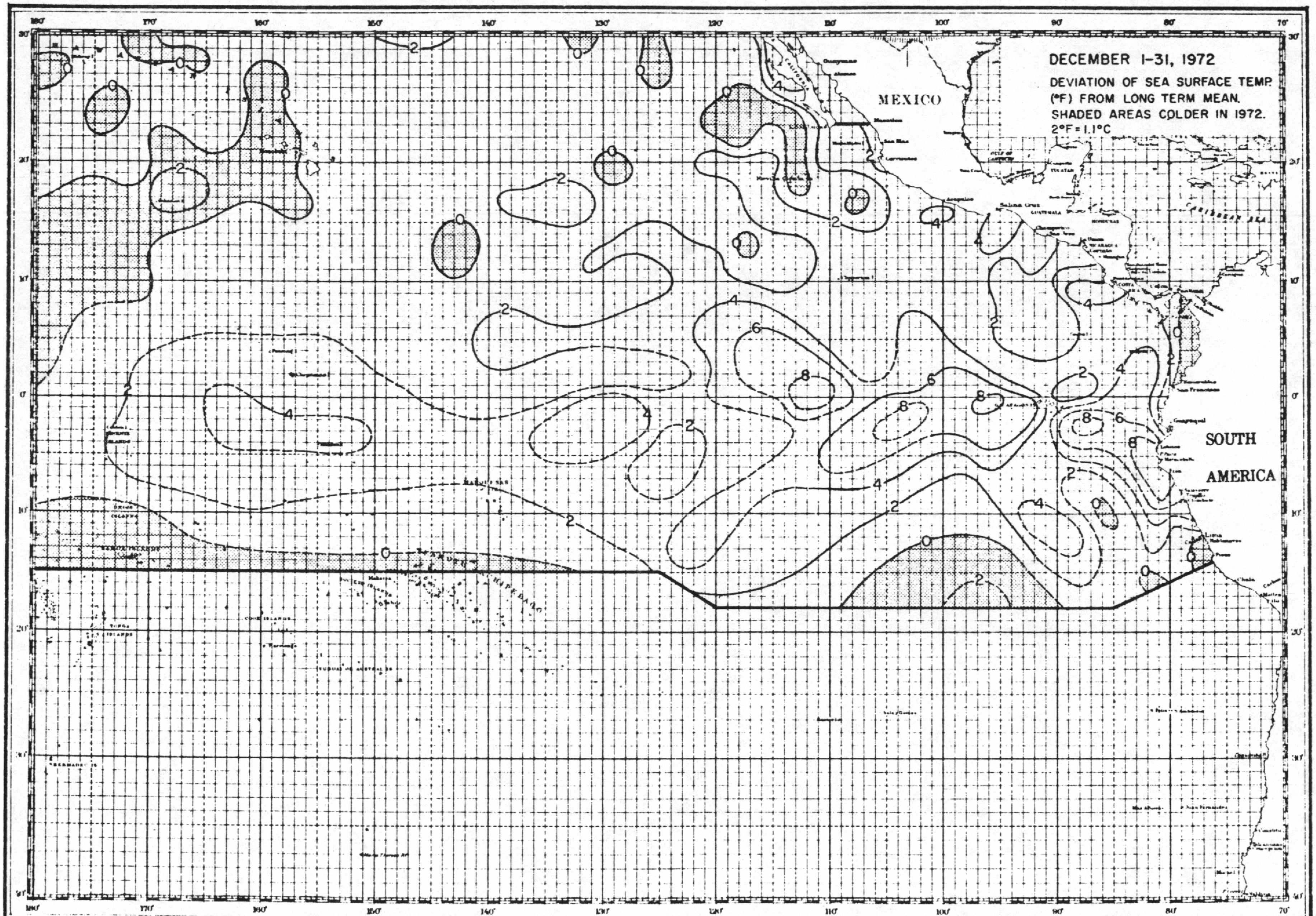

NOVEMBER 1-30, 1972
DEVIATION OF SEA SURFACE TEMP. (°F) FROM LONG TERM MEAN. SHADED AREAS COLDER IN 1972.
MEXICO
SOUTH AMERICA

Fig. 21



DECEMBER 1-31, 1972
DEVIATION OF SEA SURFACE TEMP. (°F) FROM LONG TERM MEAN. SHADED AREAS COLDER IN 1972.
2°F = 1.1°C
MEXICO
SOUTH AMERICA

Fig. 22

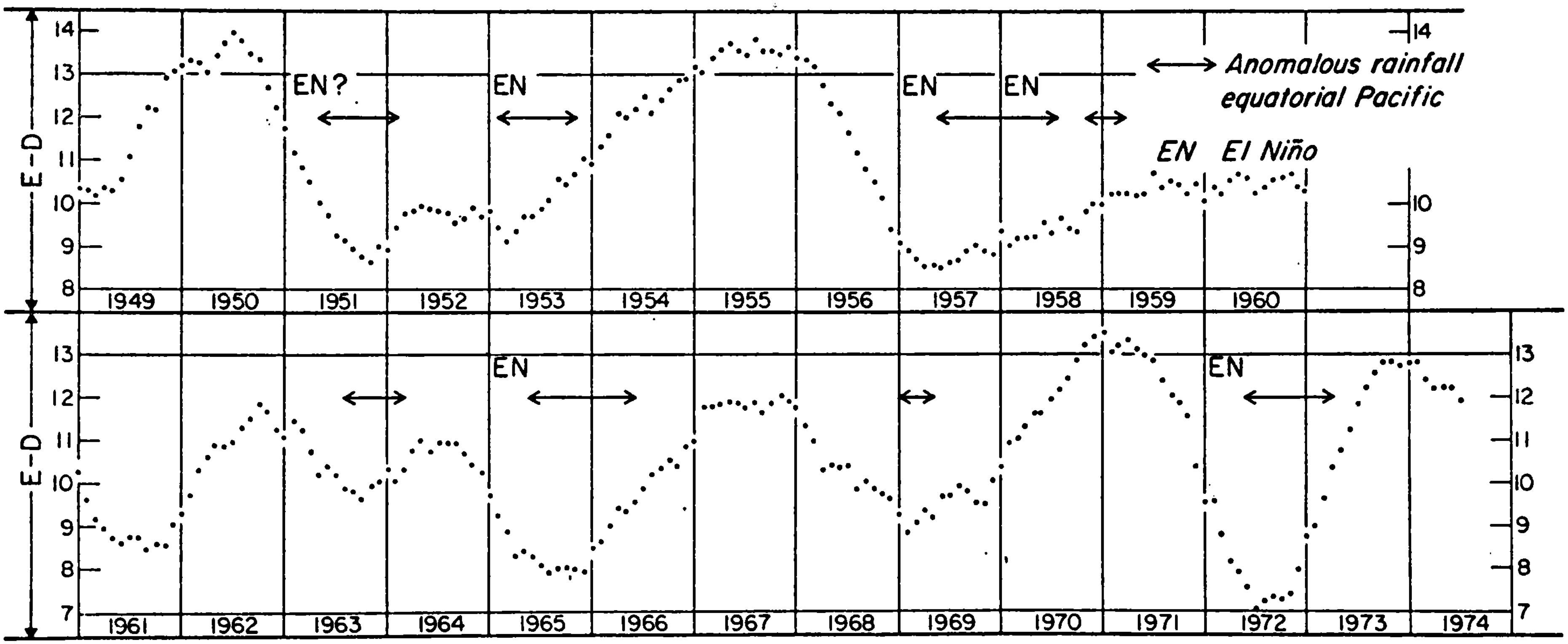


Fig. 23. The 12-month running means (points plotted at middle of the 12 months) of the difference in sea level atmospheric pressure (mb) between Easter Island and Darwin, Australia for 1949-74. Periods of El Niño and abnormally heavy central and western equatorial Pacific rainfall are indicated.

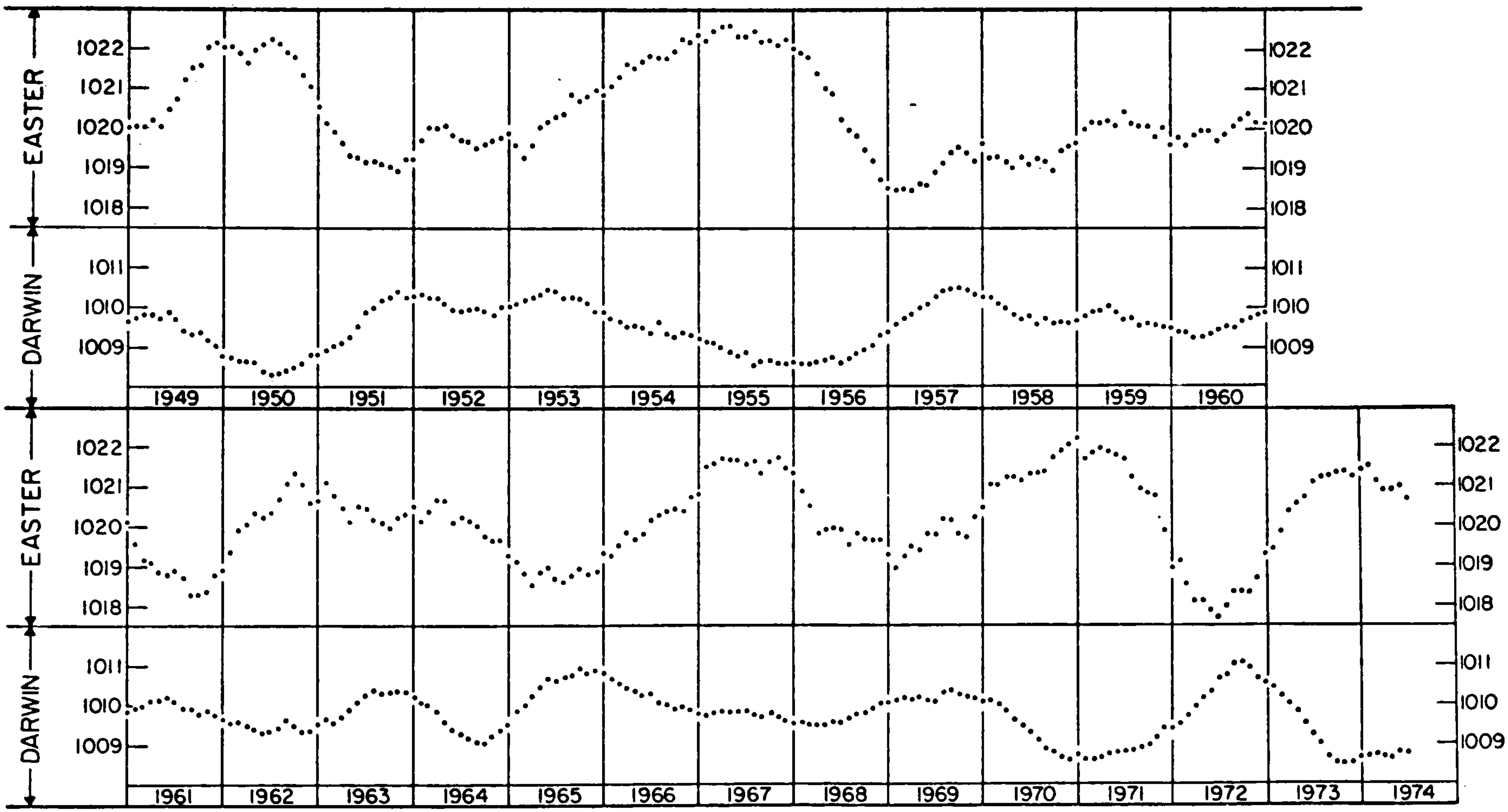


Fig. 24. The 12-month running means (points plotted at the middle of the 12 months) of sea level atmospheric pressure (mb) for Easter Island and Darwin, Australia for 1949-74.

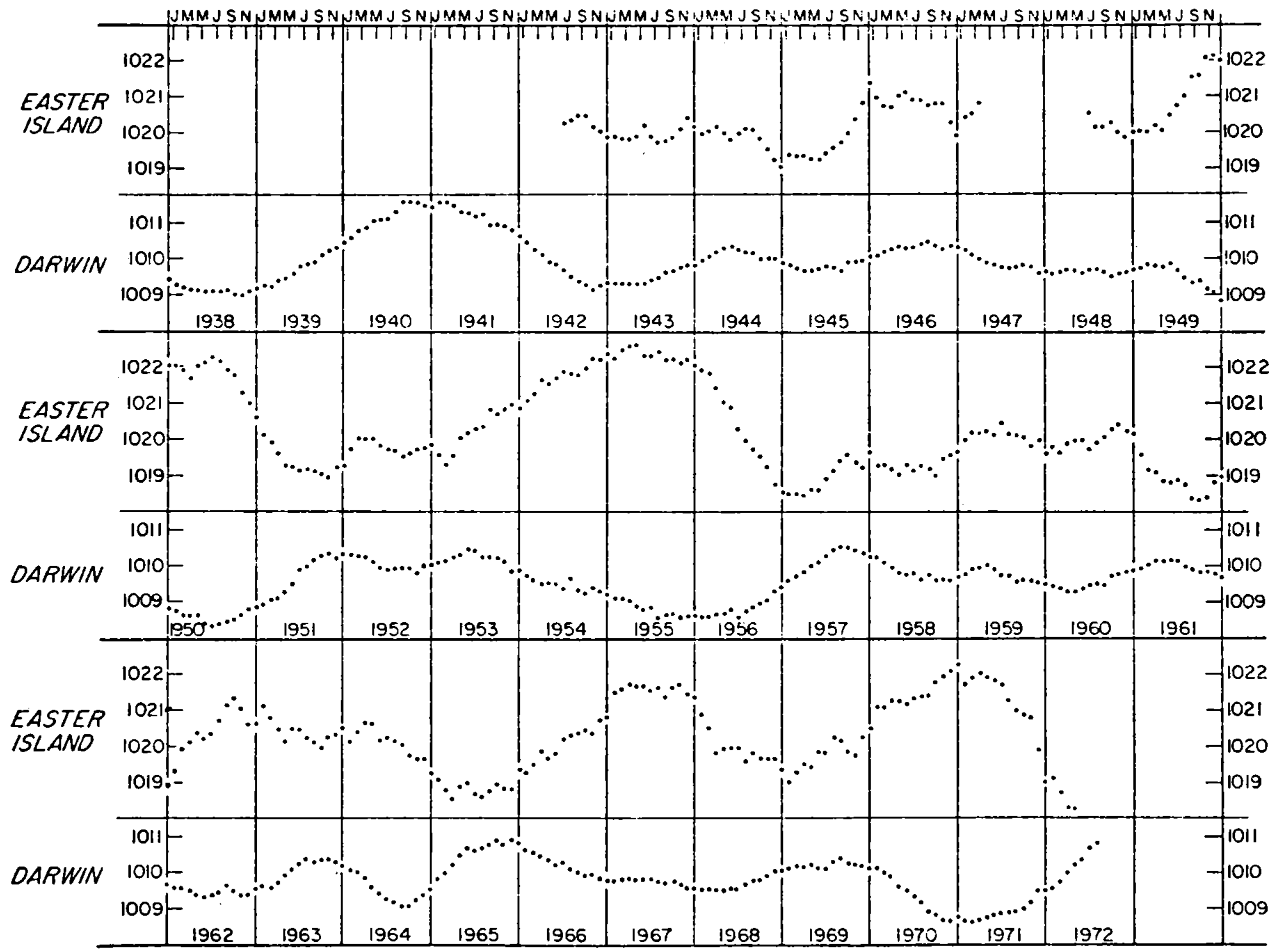


FIG. [illegible]. The 12-month running means (points plotted at middle of the 12 months) of sea level atmospheric pressure (mb) for Easter Island (1942–72) and Darwin, Australia (1938–72).

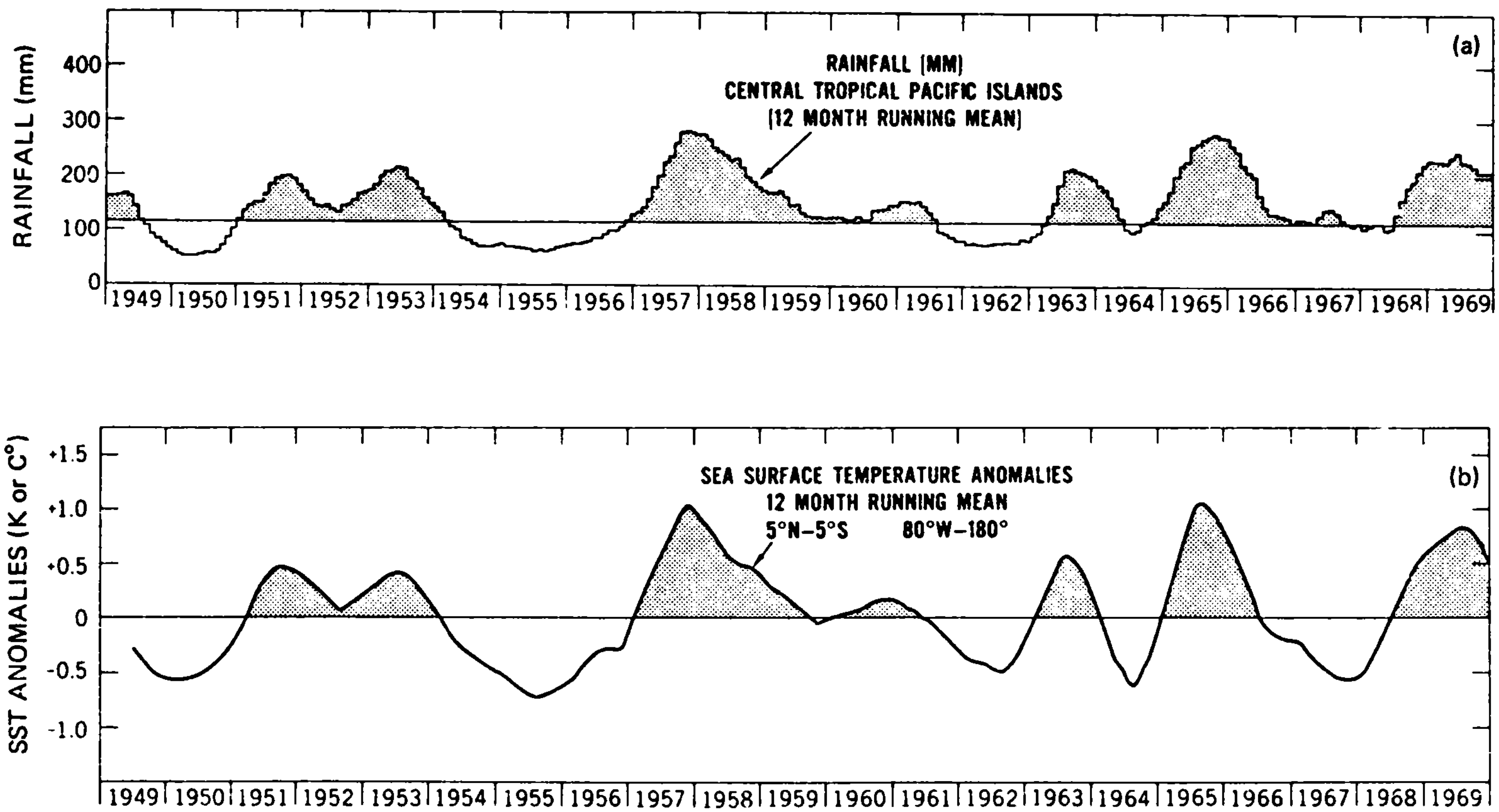


Figure 26—(a) Tropical Pacific Island rainfall (mm), 150°W to 165°E, 5°N to 5°S, 12-month running mean from 1949 to 1969; (b) SST anomalies, 5°N to 5°S, 80°W to 180°, 12-month running mean from 1949 to 1969.

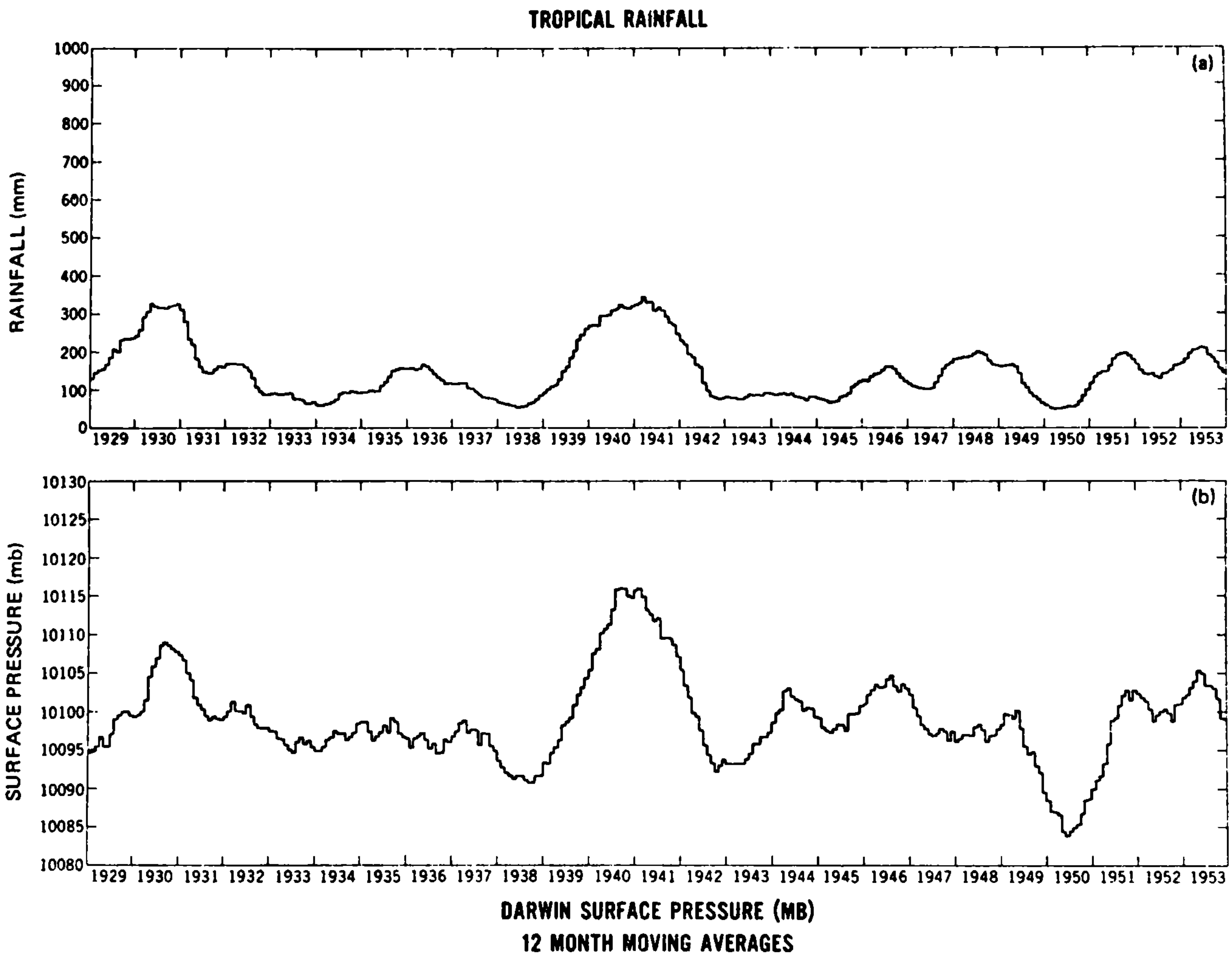


Figure 27—A comparison of 12-month running means of (a) tropical Pacific island rainfall (see Figure 6) and (b) Darwin, Australia, surface pressure from 1929 to 1953.

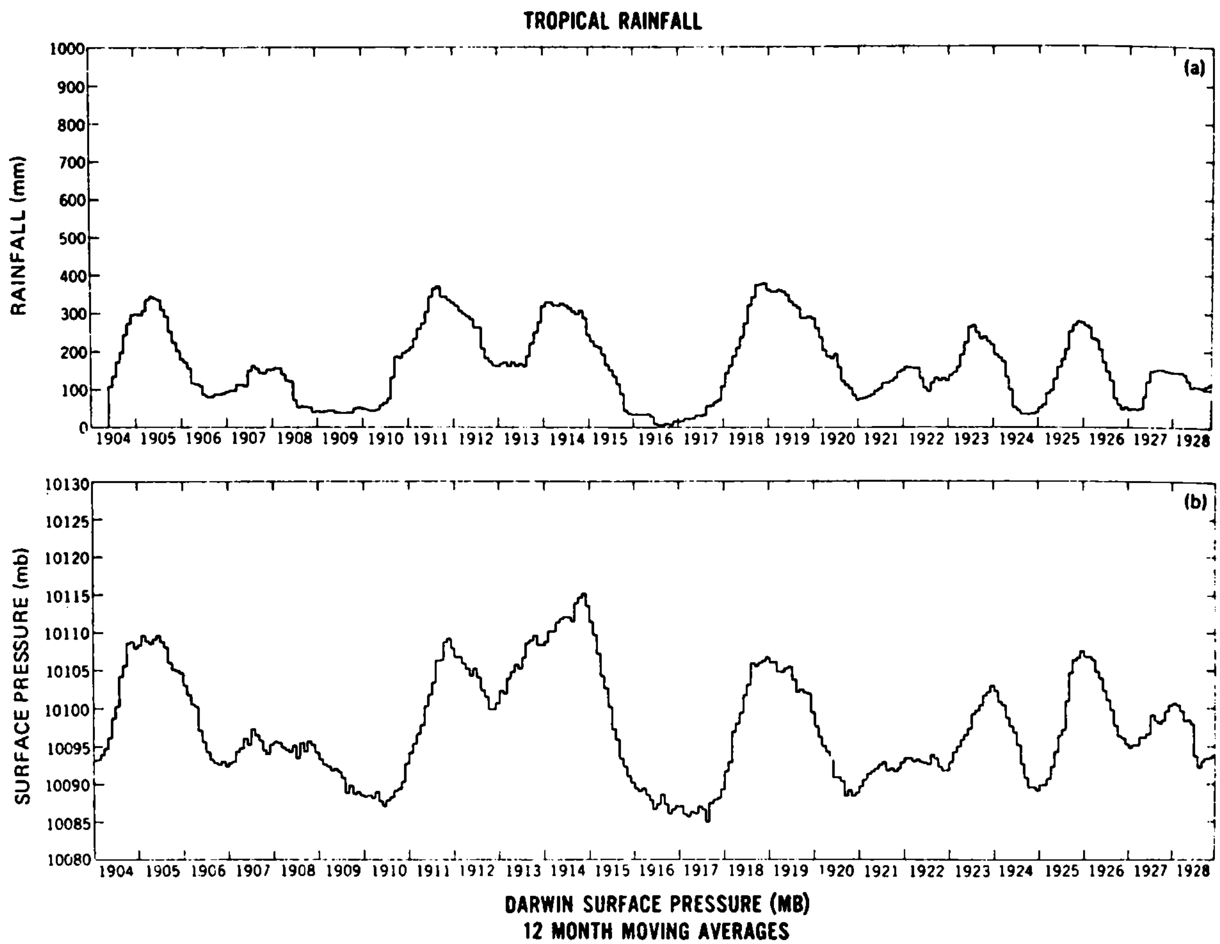


Figure 28—A comparison of 12-month running means of (a) tropical Pacific island rainfall (see Figure 6) and (b) Darwin, Australia, surface pressure from 1904 to 1928.

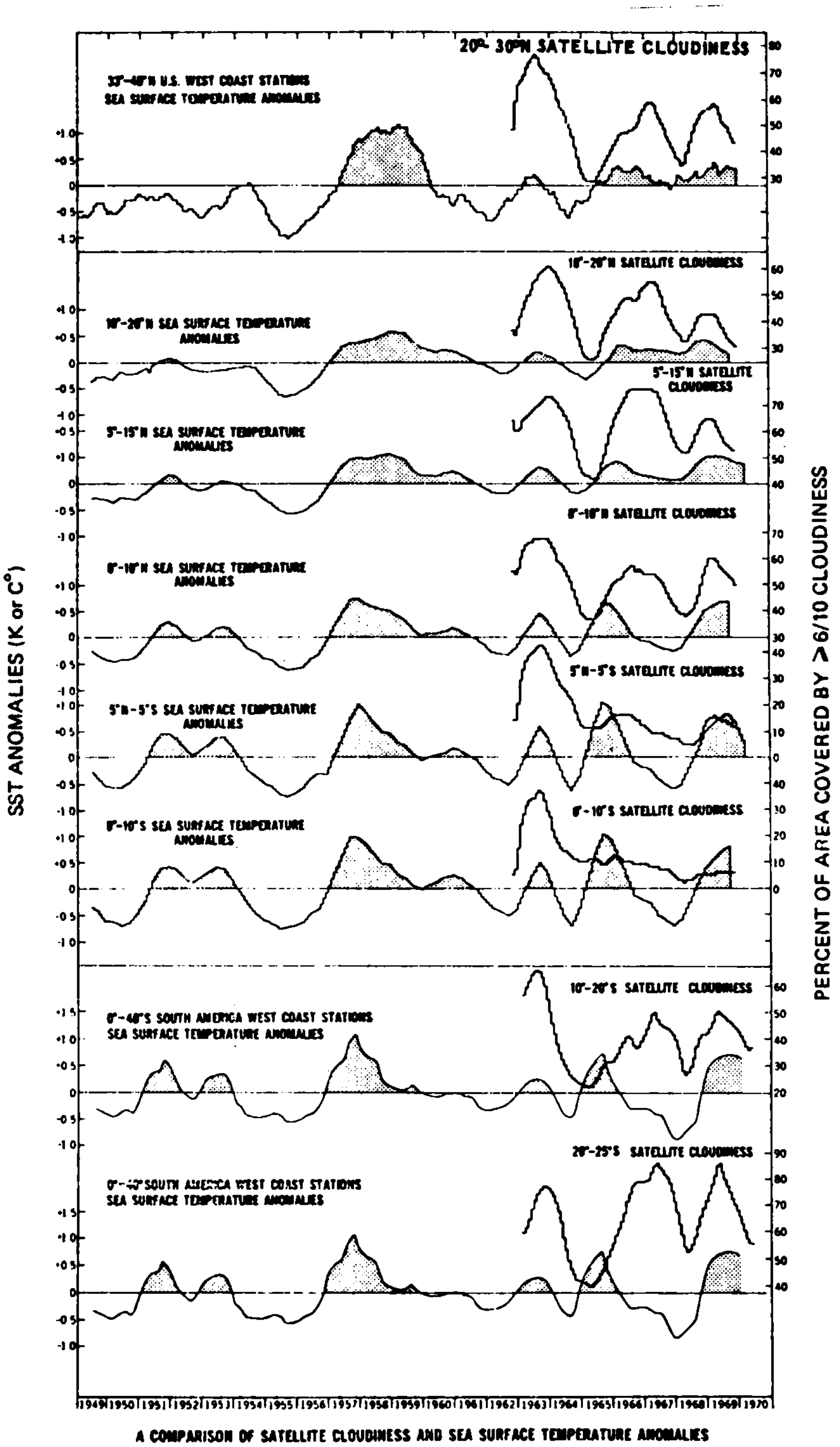
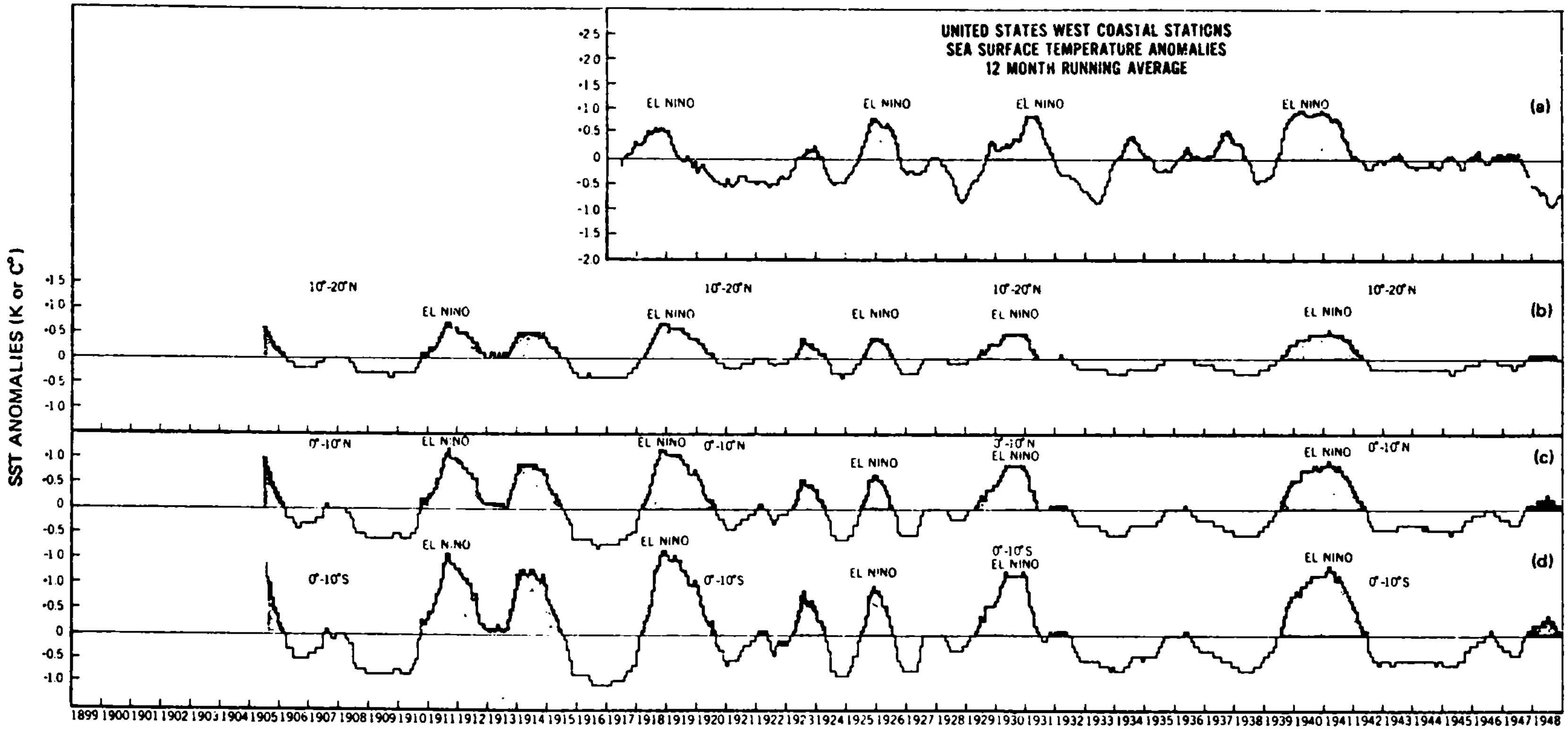
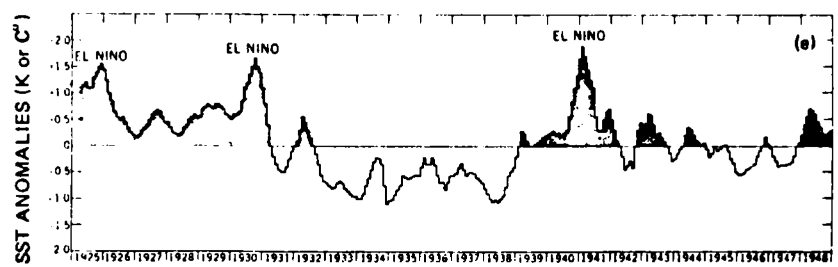


Figure 29--A comparison of 12-month running means of satellite-derived cloudiness (in percent of area covered by ≥ 6/10 clouds) from 1962 to 1970 and SST anomalies from 1949 to 1970.

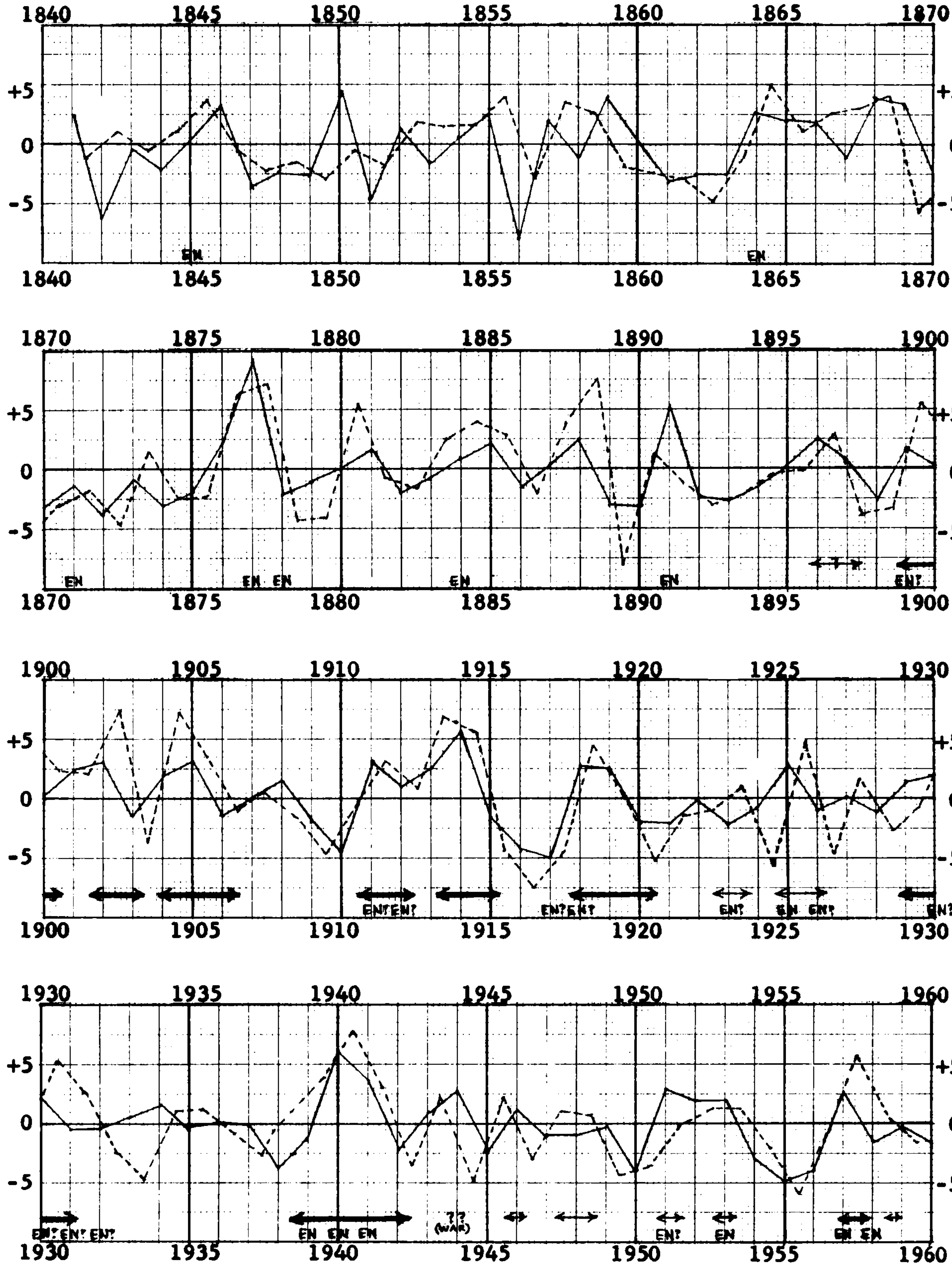


DERIVED TROPICAL PACIFIC OCEAN SEA SURFACE TEMPERATURE ANOMALIES



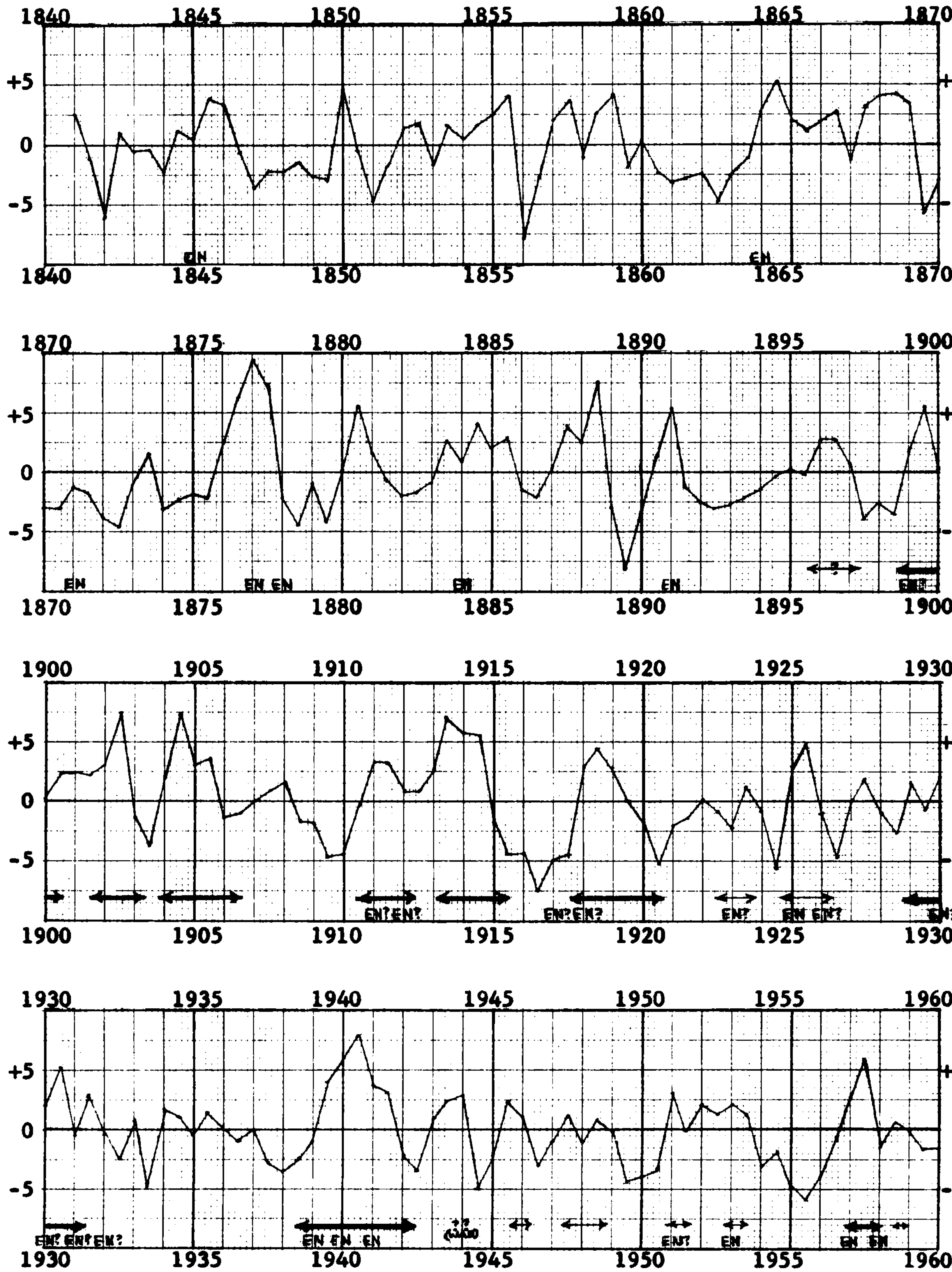
PUERTO CHICAMA, PERU
SEA-SURFACE TEMPERATURE ANOMALIES
SIX-MONTHLY RUNNING AVERAGE

Fig. 30



SOUTHERN OSCILLATION INDICES (Berlage)	EL NIÑO YEARS	EQUATORIAL PACIFIC ISLAND RAINFALL (1895-1960 only)
——— Apr-Sep - - - - - Oct-Mar	EN = Generally Accepted El Niño EN? = Some Confirming Evidence Available (see Fig. 23 and Table 1)	⟵⟶ Extensive ←→ Nonextensive (see Table 1 and Figs. 26-28)

Fig. 31



SOUTHERN OSCILLATION INDICES (Berlage) ——— Apr-Sep and Oct-Mar combined	EL NIÑO YEARS EN = Generally Accepted El Niño EN? = Some Confirming Evidence Available (see Fig. 23 and Table 1)	EQUATORIAL PACIFIC ISLAND RAINFALL (1895-1960 only) ⟵⟶ Extensive ⟵⟶ Nonextensive (see Table 1 and Figs. 26-28)

Fig. 32

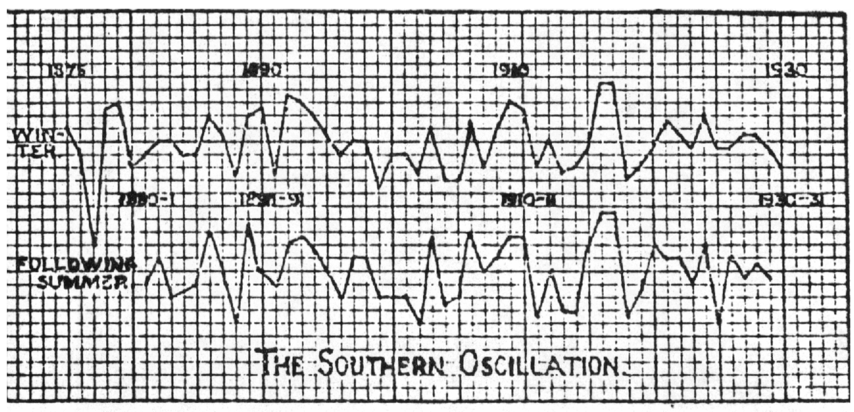
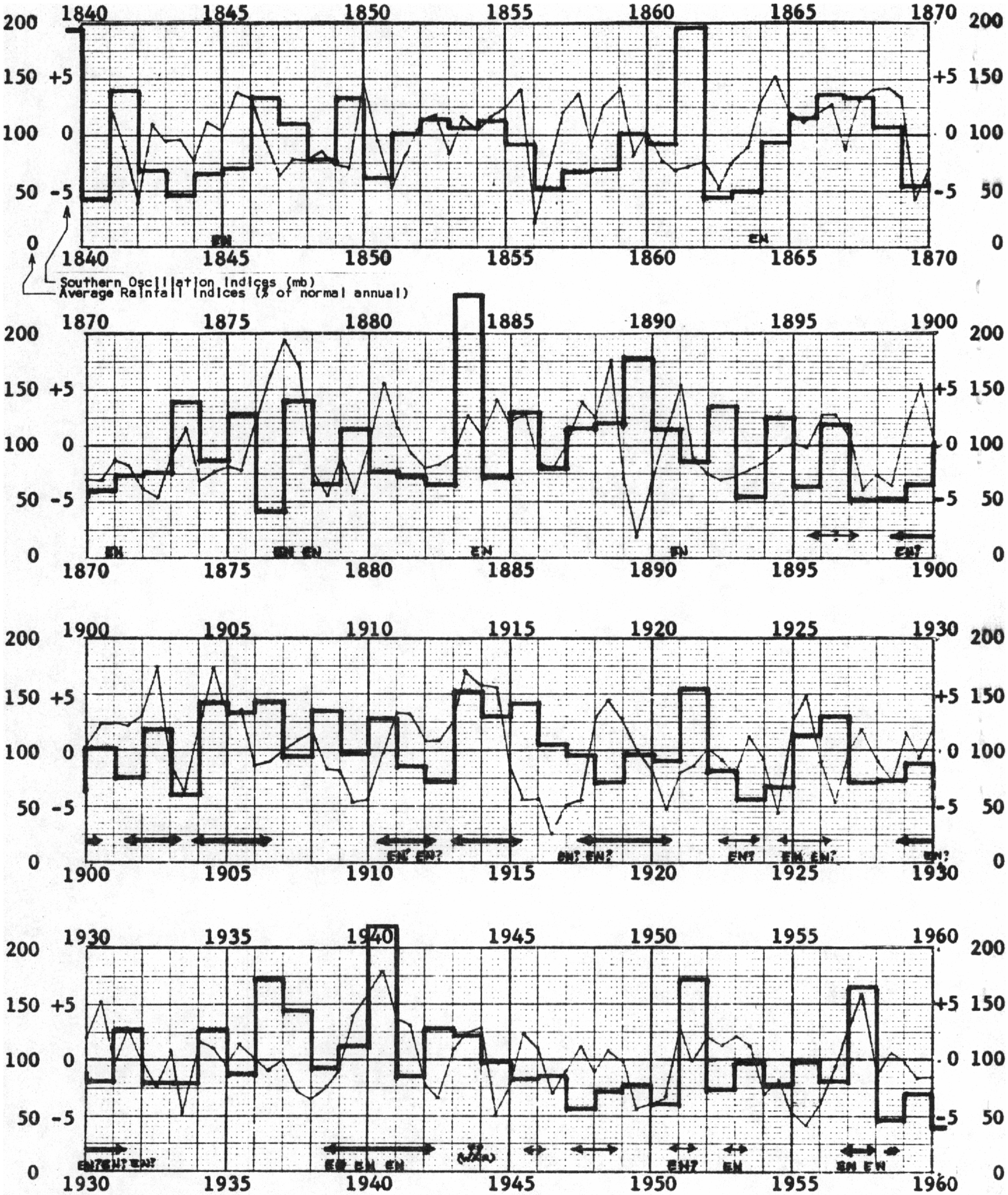


Fig. 33 (from Walker and Bliss, 1932)



SOUTHERN OSCILLATION INDICES (Berlage)	EL NIÑO YEARS	EQUATORIAL PACIFIC ISLAND RAINFALL (1895-1960 only)	AVERAGE RAINFALL INDICES
——— Apr-Sep and Oct-Mar combined	EN = Generally Accepted El Niño EN? = Some Confirming Evidence Available (see Fig. 23 and Table 1)	⟷ Extensive ⟷ Nonextensive (see Table 1 and Figs. 26-28)	1839-1930 from Lynch 1930-1961 from average % of normal rainfall at 8 So. Calif. stations

Fig. 34

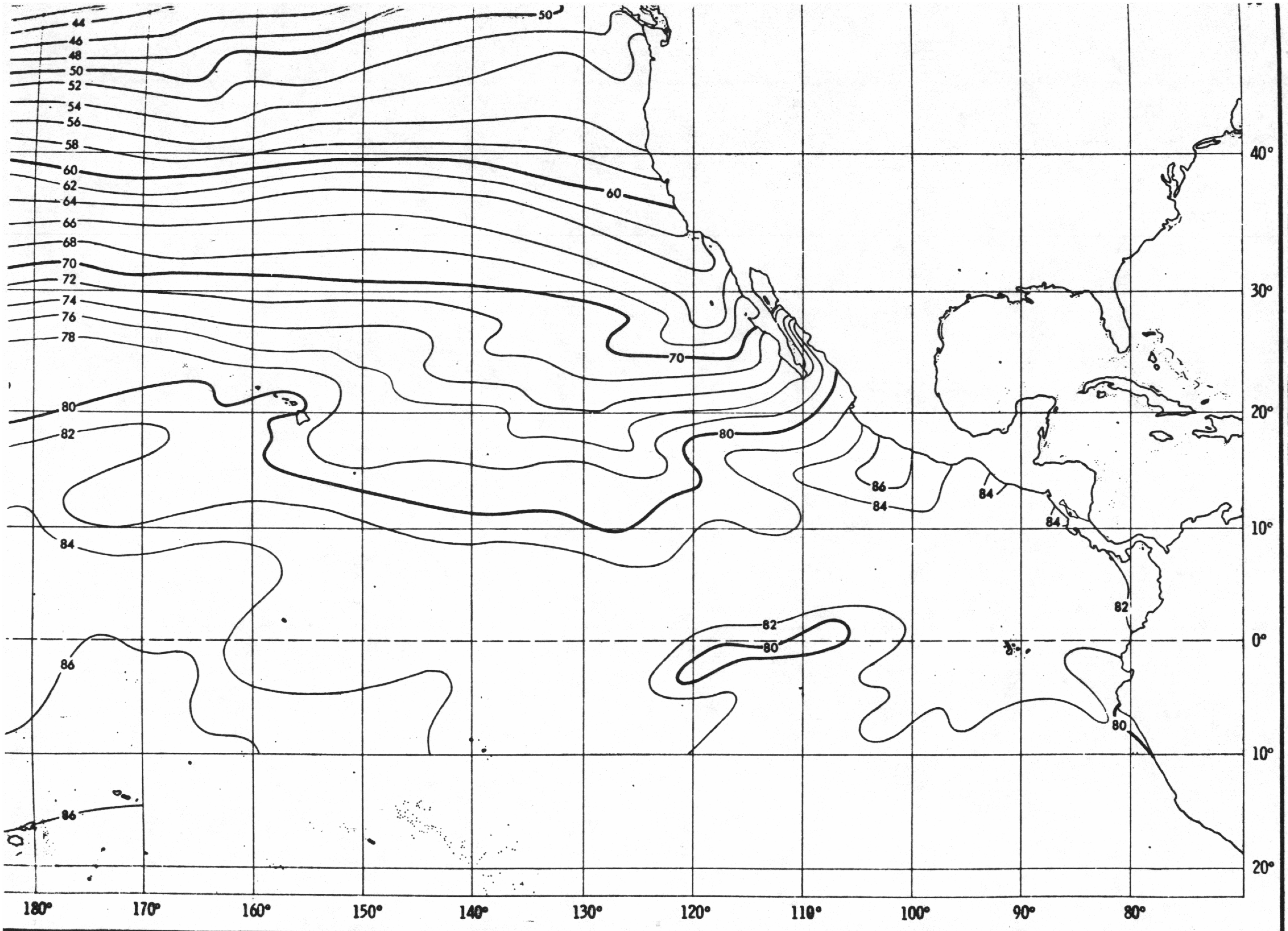


FIGURE 35 MAXIMUM SEA SURFACE TEMPERATURE (°F.), FEBRUARY

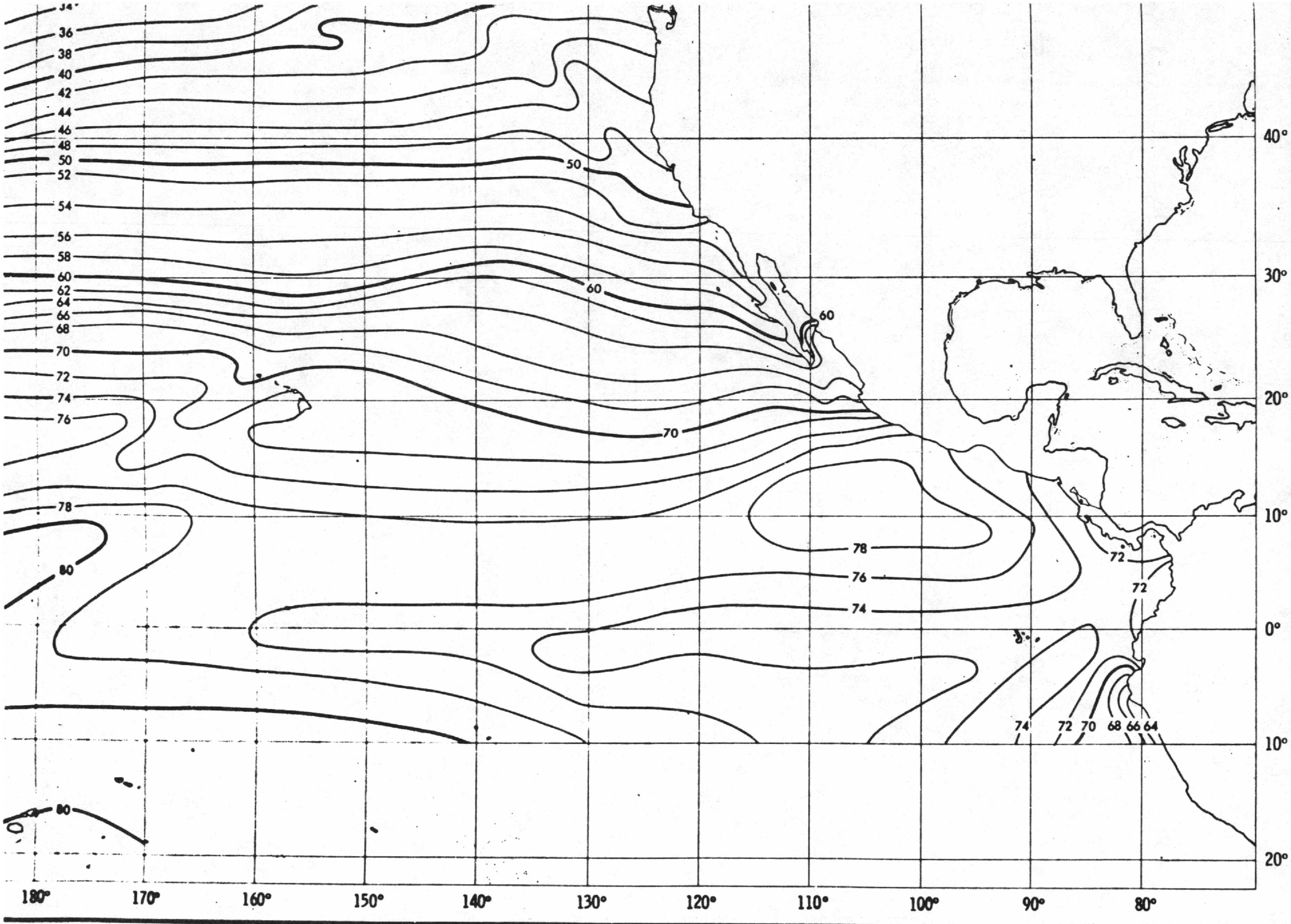


FIGURE 36 MINIMUM SEA SURFACE TEMPERATURE (°F.), FEBRUARY

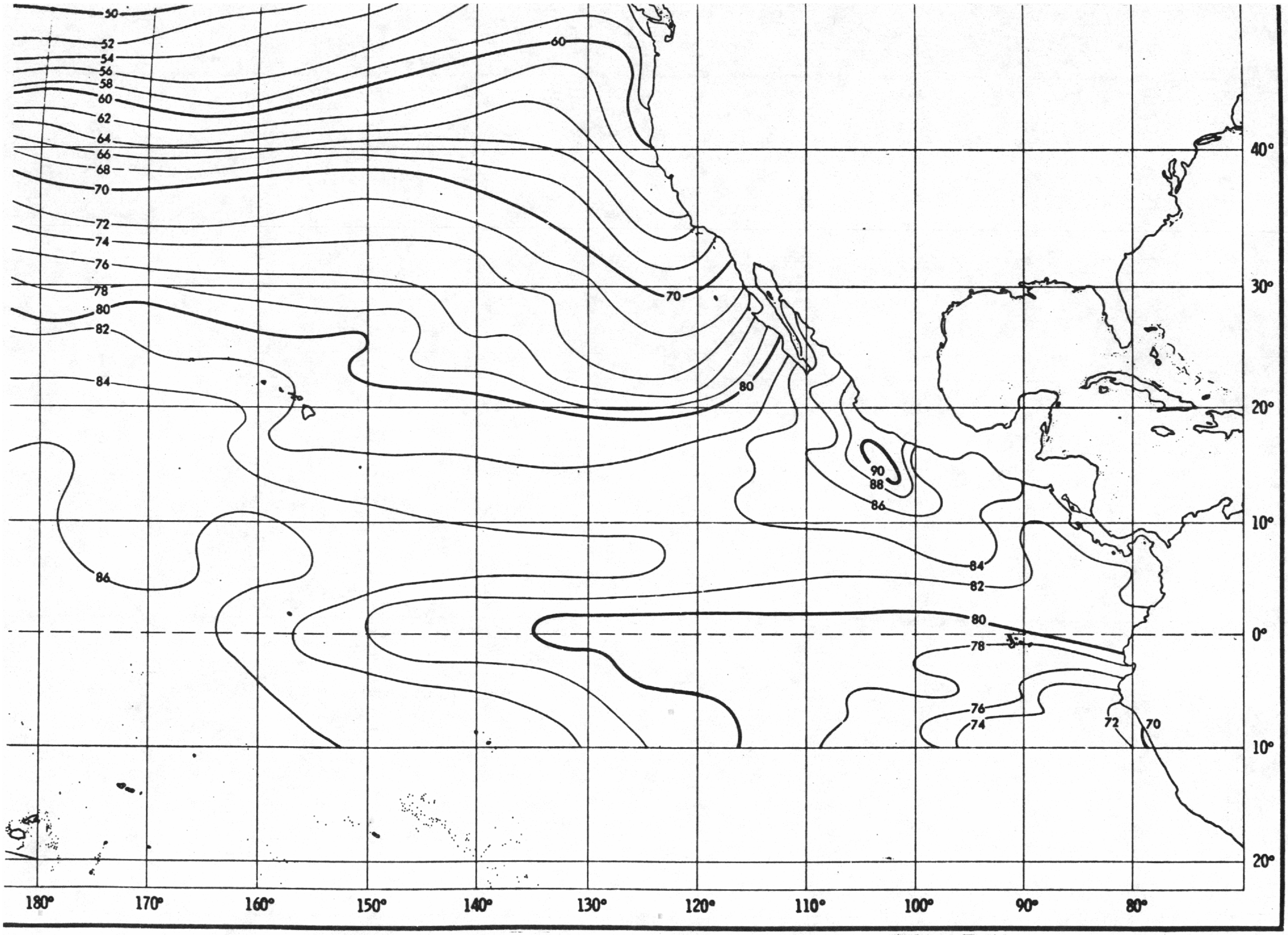


FIGURE 37 MAXIMUM SEA SURFACE TEMPERATURE (°F.), NOVEMBER

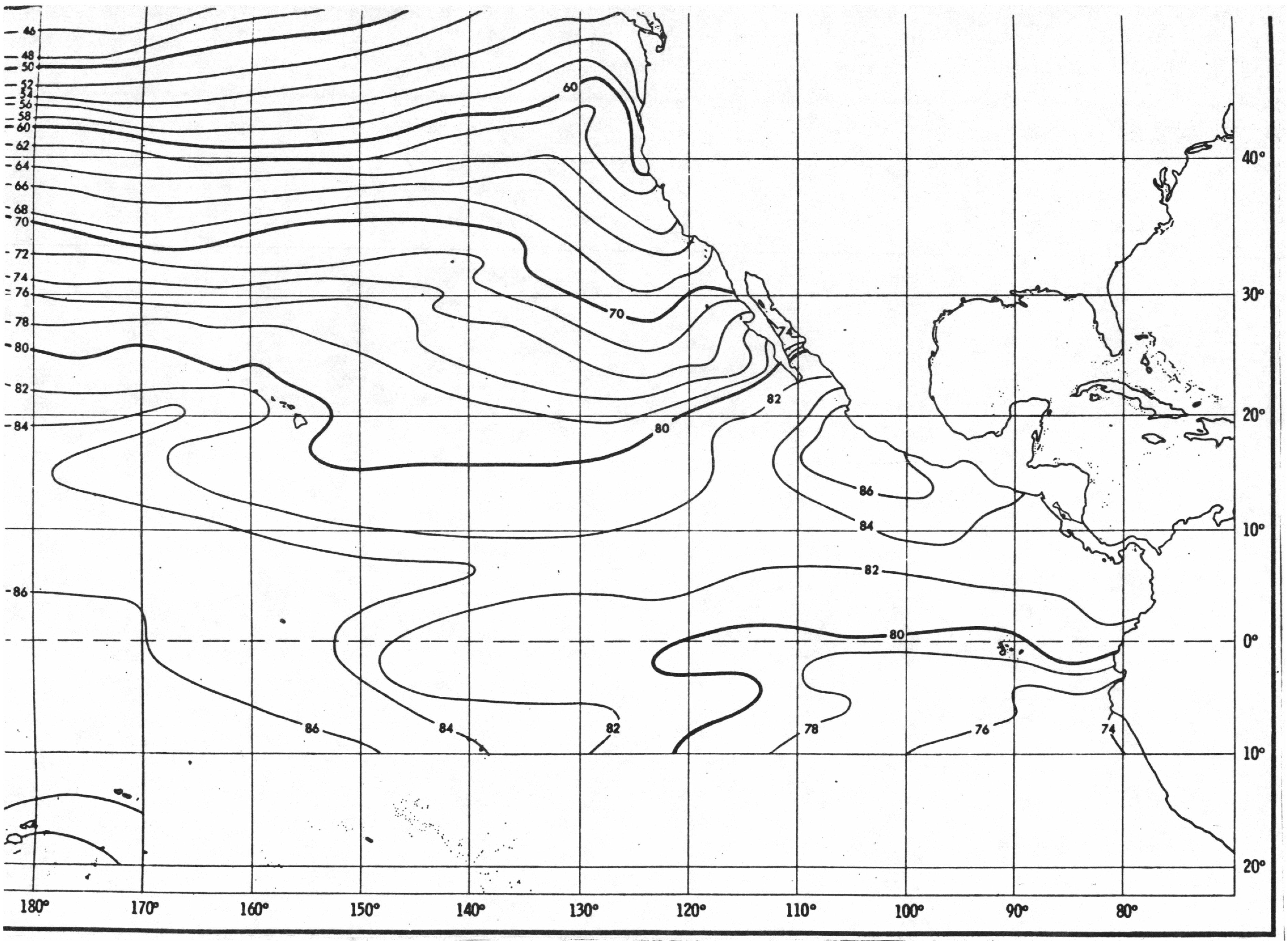
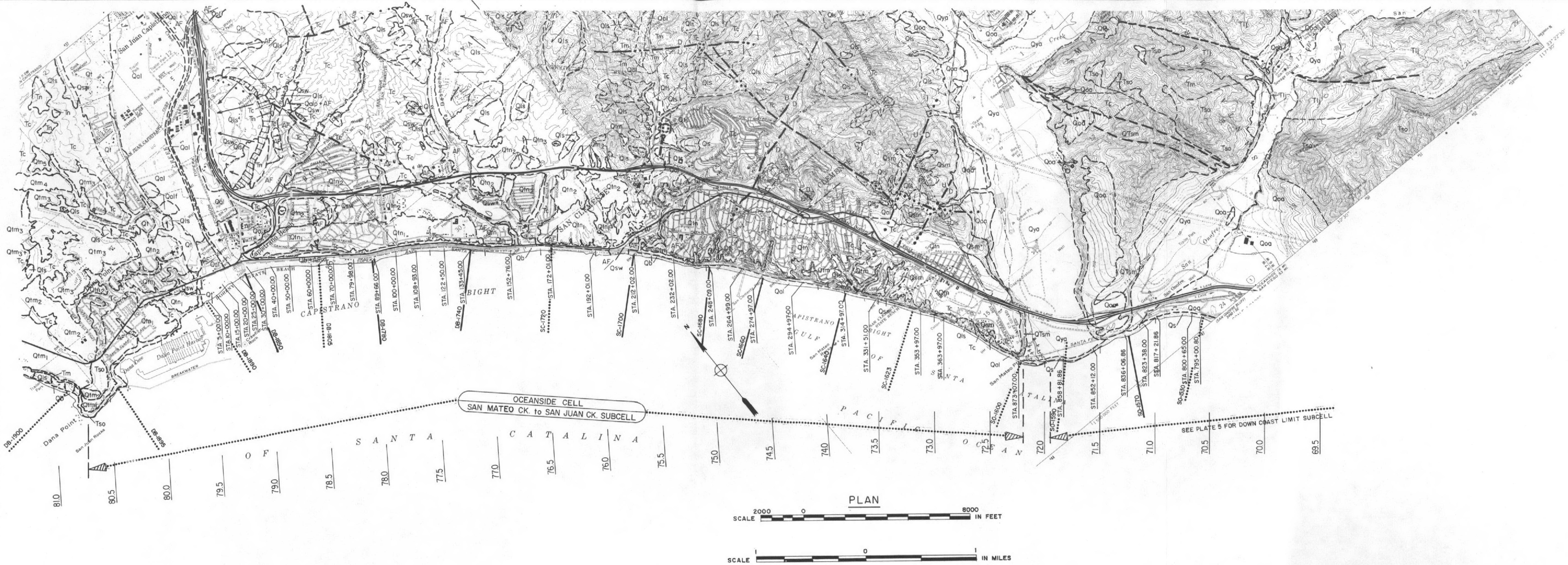


FIGURE 38 MAXIMUM SEA SURFACE TEMPERATURE (°F.), DECEMBER



LEGEND

———	BEACH PROFILE ONLY
········	BEACH PROFILE PLUS SEDIMENT SAMPLING
×	OFFSHORE SEDIMENT STAKE
①	WAVE GAGE

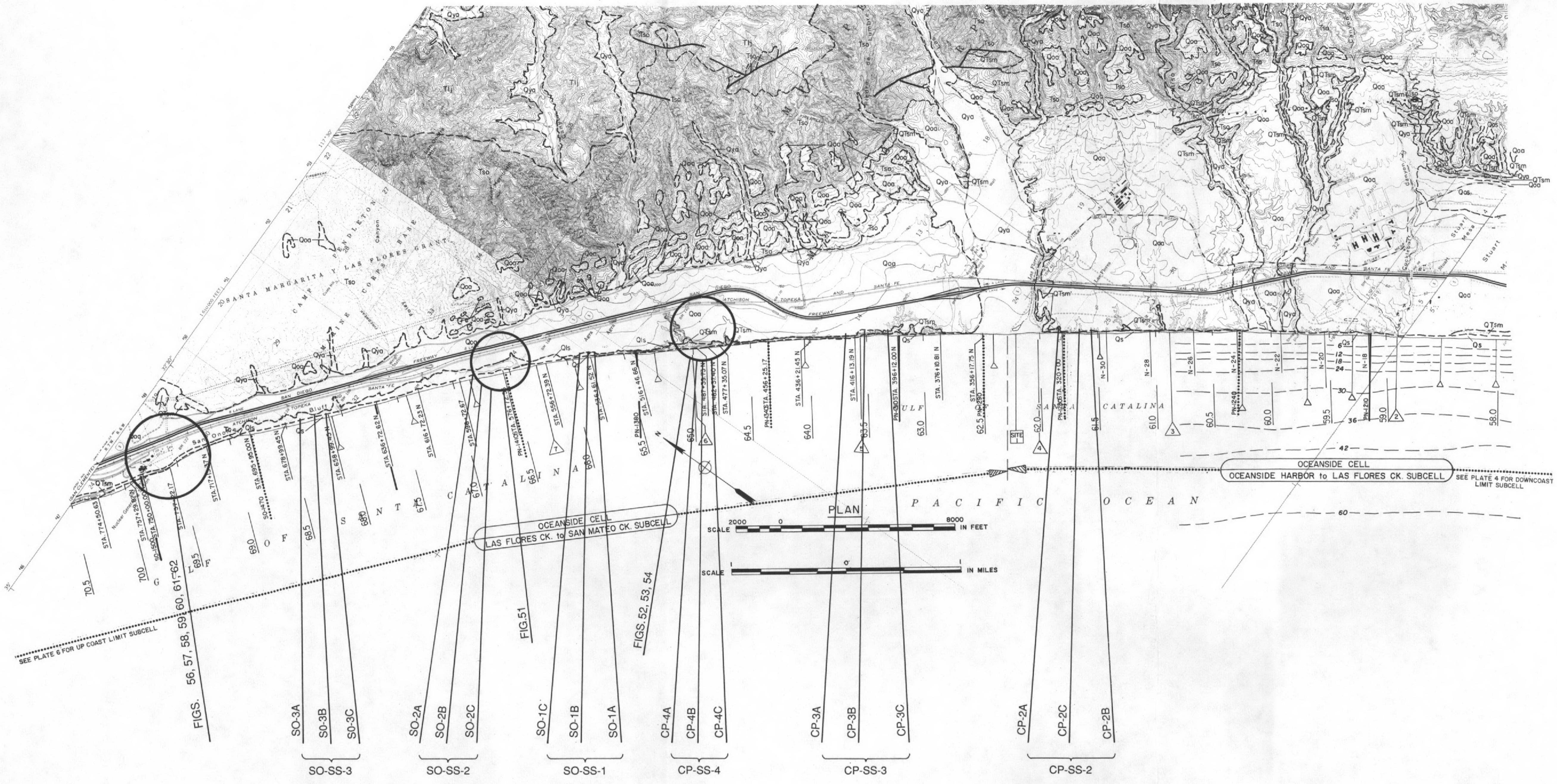
COAST OF CALIFORNIA STORM AND TIDAL WAVES STUDY

DANA POINT TO MEXICAN BORDER

LOCATION MAP

SAN ONOFRE (MI. 70.5) TO DANA POINT (MI. 80.5)

U. S. ARMY CORPS OF ENGINEERS
LOS ANGELES DISTRICT



NOTES:
1. See text and figures 51 through 62 for detailed description of the location and extent of cliff erosion.

LEGEND
SS SAMPLE SITE SO SAN ONOFRE CP CAMP PENDLETON TP TORREY PINES

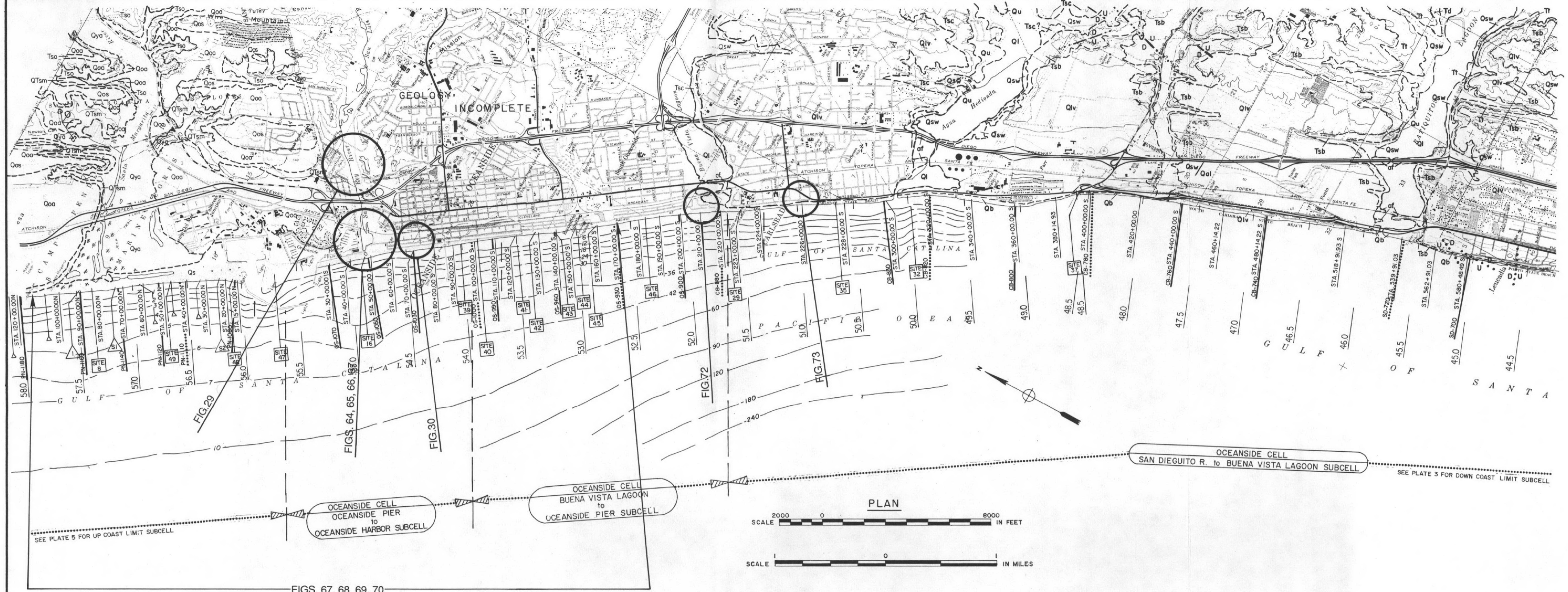
COAST OF CALIFORNIA STORM AND TIDAL WAVES STUDY

DANA POINT TO MEXICAN BORDER

LOCATION MAP

SANTA MARGARITA RIVER (MI. 58.0) TO SAN ONOFRE (MI. 70.5)

U. S. ARMY CORPS OF ENGINEERS
LOS ANGELES DISTRICT



NOTES:
1. See text and figures 29 through 73 for detailed description of the location and extent of cliff erosion.

LEGEND

- BEACH PROFILE ONLY
- BEACH PROFILE PLUS SEDIMENT SAMPLING
- × OFFSHORE SEDIMENT STAKE
- WAVE GAGE

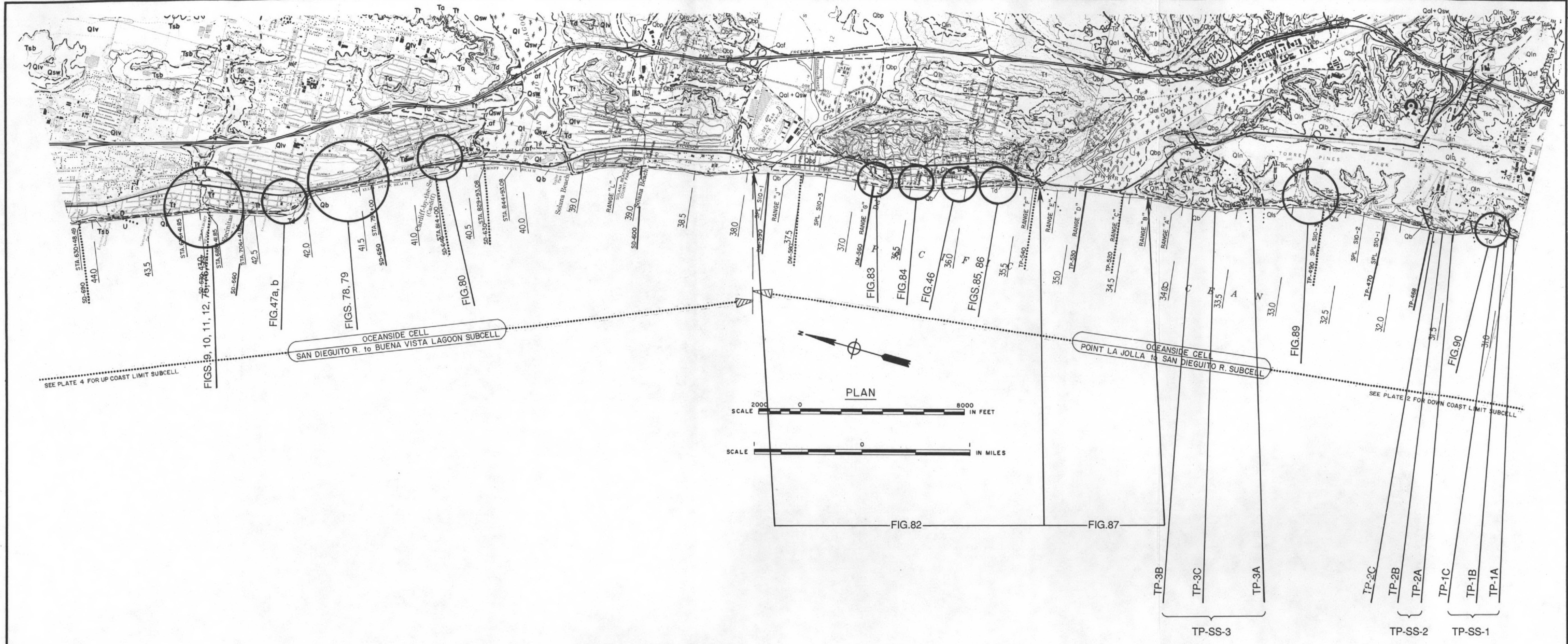
COAST OF CALIFORNIA STORM AND TIDAL WAVES STUDY

DANA POINT TO MEXICAN BORDER

LOCATION MAP

LEUCADIA (MI. 44.0) TO SANTA MARGARITA RIVER (MI. 58.0)

U. S. ARMY CORPS OF ENGINEERS
LOS ANGELES DISTRICT



NOTES:
1. See text and figures 9 through 90 for detailed description of the location and extent of cliff erosion.

LEGEND

SS SAMPLE SITE
SO SAN ONOFRE
CP CAMP PENDLETON
TP TORREY PINES

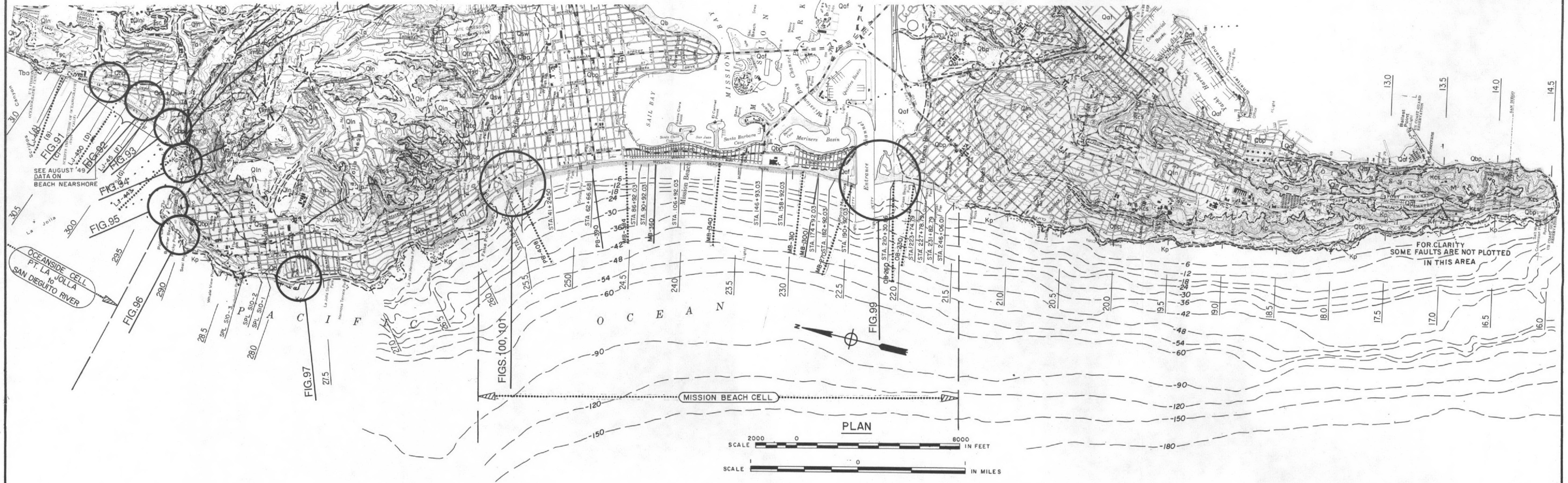
COAST CALIFORNIA STORM AND TIDAL WAVES STUDY

DANA POINT TO MEXICAN BORDER

LOCATION MAP

LA JOLLA (MI. 31.0) TO LEUCADIA (MI. 44.0)

U. S. ARMY CORPS OF ENGINEERS
LOS ANGELES DISTRICT



NOTES:
1. See text and figures 91 through 99 for detailed description of the location and extent of cliff erosion.

LEGEND	
——	BEACH PROFILE ONLY
········	BEACH PROFILE PLUS SEDIMENT SAMPLING
×	OFFSHORE SEDIMENT STAKE
①	WAVE GAGE

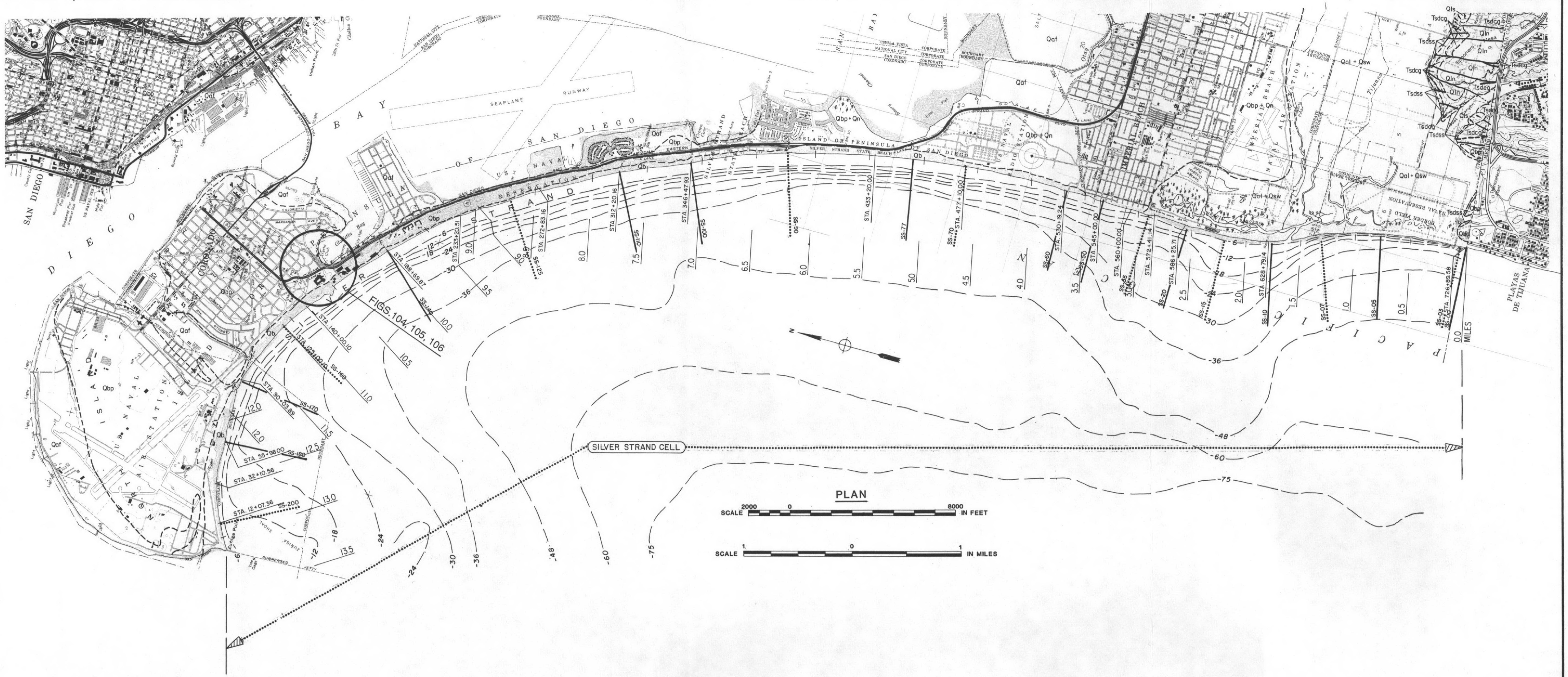
COAST OF CALIFORNIA STORM AND TIDAL WAVES STUDY

DANA POINT TO MEXICAN BORDER

LOCATION MAP

POINT LOMA (MI. 14.0) TO LA JOLLA (MI. 31.0)

U. S. ARMY CORPS OF ENGINEERS
LOS ANGELES DISTRICT



NOTES:
1. See text and figures 104 through 106 for detailed description of the location and extent of cliff erosion.

LEGEND	
———	BEACH PROFILE ONLY
....	BEACH PROFILE PLUS SEDIMENT SAMPLING
×	OFFSHORE SEDIMENT STAKE
②	WAVE GAGE

COAST OF CALIFORNIA STORM AND TIDAL WAVES STUDY

DANA POINT TO MEXICAN BORDER

LOCATION MAP

MEXICAN BORDER (MI. 0.0) TO ZUNIGA JETTY (MI. 13.2)

U. S. ARMY CORPS OF ENGINEERS
LOS ANGELES DISTRICT