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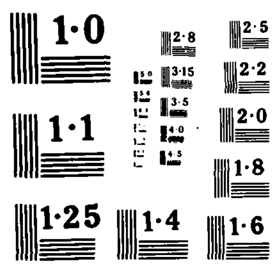
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US Army Corps of Engineers
Los Angeles District

COAST OF CALIFORNIA
STORM AND TIDAL WAVES STUDY

GEOMORPHOLOGY FRAMEWORK REPORT MONTEREY BAY

CCSTWS 85-2
December 1985

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

THIS REPORT SUMMARIZES THE PUBLISHED DATA RELATING TO THE LITTORAL ZONE OF MONTEREY BAY, CALIFORNIA. THE REPORT IS PUBLISHED AS PART OF THE COAST OF CALIFORNIA STORM AND TIDAL WAVES STUDY CURRENTLY BEING CONDUCTED BY THE U.S. ARMY CORPS OF ENGINEERS, LOS ANGELES DISTRICT.

AN INTERPRETATION OF MORPHODYNAMIC PROCESSES FOR THE AREA IS DEVELOPED USING AVAILABLE INFORMATION ON THE DISTRIBUTION, COMPOSITION AND MOVEMENT OF LITTORAL ZONE SEDIMENTS; TEXTURE, COMPOSITION AND SUPPLY RATE OF SEDIMENTS FROM THE THREE ADJACENT DRAINAGE BASINS; THE COMPOSITION, DISTRIBUTION

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AND RETREAT RATES OF THE COASTAL CLIFFS AND DUNES; AND THE GEOLOGIC AND TECTONIC HISTORY OF THE REGION. BECAUSE THERE IS INSUFFICIENT DATA TO MAKE A QUANTITATIVE MODEL, THE REPORT CONCLUDES WITH RECOMMENDATIONS FOR FUTURE SCIENTIFIC STUDIES THAT WOULD LEAD TO A MORE QUANTITATIVE MODEL THAT INTERESTED AGENCIES COULD EFFECTIVELY USE WHEN DEALING WITH COASTAL EROSION PROBLEMS WITHIN THE BAY.

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GEOMORPHOLOGY FRAMEWORK REPORT
MONTEREY BAY
Ref. No. CCSTWS 85-2

Coast of California Storm and Tidal Waves Study

U.S. Army Corps of Engineers
Los Angeles District, Planning Division
Coastal Resources Branch
P.O. Box 2711
Los Angeles, California 90053

DECEMBER 1985

prepared by

U.S. Geological Survey
Menlo Park, California

SUMMARY

This report summarizes the published data relating to the littoral zone of Monterey Bay, California. An interpretation of morphodynamic processes for the area is developed using available information on the distribution, composition, and movement of littoral zone sediments; texture, composition, and supply rate of sediments from the three adjacent drainage basins; the composition, distribution and retreat rates of the coastal cliffs and dunes; and the geologic and tectonic history of the region. Because there is insufficient data to make a quantitative model, the report concludes with recommendations for future scientific studies that would lead to a more quantitative model that interested agencies could effectively use when dealing with coastal erosion problems within the bay.

Monterey Bay is located along the central California coast about 100 km south of San Francisco; it is the largest open embayment along that section of coast. For the purpose of this study, the bay extends from Point Santa Cruz on the north to Point Piños on the south. Population density is high in the northern and southern ends of the bay and low in the center. Though the coastline appears to have an equilibrium shape, much of the bay's coast is actively eroding. In the northern part of the bay, erosion is threatening many coastal homes, and local homeowners and governments have had to emplace protective structures. In the south-central part of the bay, erosion rates are even greater but have been given less attention until recently because of the lack of dwellings in that area.

The north shore of Monterey Bay contains several small beaches that often disappear during winter storms. The beaches are usually backed by cliffs that easily erode under direct wave attack. Southward littoral drift from north of Point Santa Cruz supplies most of the beach sand to this area, but the San Lorenzo River episodically supplies significant amounts of sand. The contribution of sand from cliff erosion along the north shore is small. For the most part, the median grain size of the beach sand is in the medium-fine sand range (0.25 mm). Though the west jetty at the mouth of Santa Cruz Harbor initially stopped longshore sand transport , most of the sand currently bypasses the harbor. There are no major sediment sinks along the bay's northern shore.

The eastern shore of Monterey Bay can be divided into two long beaches that are separated by the head of Monterey Submarine Canyon at Moss Landing. Sand is supplied to the northern area by southward littoral transport and from the Pajaro River. The amount of sand supplied by erosion of the coastal cliffs, although slightly higher than along the north shore beaches, is still relatively low. The median grain size of the beach sands ranges from 0.25 mm in the north to about 0.50 mm at Moss Landing. Apparently, all the southward-moving littoral sand enters Monterey Canyon, where it is permanently lost from the littoral zone.

South of Moss Landing the eastern shore consists of sand delivered to the coast by the Salinas River and of sand eroded from the unconsolidated and semiconsolidated dunes on the landward edge of the beach. The median grain size of the beach sand increases to the south from Moss Landing, reaching a maximum at Ft. Ord (0.9 mm); grain size decreases rapidly from there to Monterey Harbor (0.2 mm). Sinks for the littoral zone sand include Monterey Canyon, the Salinas River delta, coastal sand mining, and, perhaps, offshore transport.

The southern shore of Monterey Bay contains pocket beaches composed of sand from the local granitic outcrops. Littoral transport and coastal erosion are both very low.

To properly approach the problem of coastal erosion along the Monterey Bay beaches, sand supply and transport rates will have to be better understood. Appropriate studies that should be conducted include the following:

1. Determine more accurately the volume of sand supplied by the various sources–rivers, cliffs, littoral transport from north of Point Santa Cruz, and transport from the offshore zones.

2. Estimate the variability in the supply rate, which is related to episodic flooding and cliff erosion.

3. Determine the thickness and movement of littoral-zone sand throughout the bay.

4. Measure the on-offshore transport.

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1. Monterey Bay and vicinity

1. INTRODUCTION

1.1. This report describes the geological, geomorphological, and physical processes that affect the littoral zone of Monterey Bay, California. Information for this report comes from the published literature pertaining to the bay and to the adjacent land from which the bay's sediments are supplied. Most of the area discussed herein is shown on Plate 1, and the entire area is discribed in the appropriate chapters. Chapters two through four summarize the scientific papers pertaining to littoral-zone resources, the drainage system that supplies sediment to the bay, the coastal cliffs that rim most of the bay, and the neotectonics and geology of the bay. The sixth chapter uses that data to form a morphodynamic model based on the concept of a littoral cell. The next chapter gives recommendations for future field studies in the area.

1.2. This report has been prepared by J. R. Dingler, B. L. Laband, and R. J. Anima of the U. S. Geological Survey and edited by the Los Angeles District, U. S. Army Corps of Engineers. The report is part of the Coast of California Storm and Tidal Waves Study managed by the Corps of Engineers.

Reason for the Study

1.3. The information given here will support a variety of tests described in the Coast of California Storm and Tidal Waves' Plan of Study (U.S. Army, 1983). Existing sedimentologic data that aid in describing the types of material in transit in the littoral zone will be of assistance in planning the execution of Task IC, Beach and Shoreface Profiles; and Task ID Sediment Sampling. The river basins section will support Task IF, River Sediment Discharge, and Task IIF, Historic Land Use and Human Influence at the Coast. The coastal cliffs section will support Task IG, Bluff-Derived Sediments. Data and observations on the region's tectonic activity and geologic structure will provide initial input to Task IIE, Historic Water Levels. Sand and gravel mining data will aid in furnishing initial information to Task IIF, Historic Land Use and Human Influence at the Coast.

Purpose and Scope

1.4. The Coast of California Storm and Tidal Waves Study will collect and analyze basic oceanographic, meteorologic, and geologic data to form a basis to define and assess coastal changes. This report, which summarizes the geologic, geomorphologic, and tectonic data on Monterey Bay, California, will serve as a guide in planning future field-collecting activities, laboratory testing, and office analyses used to document geological conditions of erosion and mechanisms of sediment transport. The boundaries of this framework study are Point Santa Cruz to the north and Point Piños to the south.

1.5. Recommendations are made for studies that will provide data to answer questions discovered during this study. That data will be required before coastal geologists, engineers, and planners can successfully undertake remedial measures to control beach erosion in the study area.

Authority

1.6. This storm and tidal wave study is being undertaken pursuant to Section 208, of the Flood Control Act of 1965, Public Law 89-298. The authorization dated 27 October 1965, reads in part as follows:

> SEC. 208. The Secretary of the Army is hereby authorized and directed to cause surveys for flood control and allied purposes, including channel and major drainage improvements, and floods aggravated by or due to wind or tidal effects, to be made under the direction of the Chief of Engineers, in drainage areas of the United States and its territorial possessions, which include the localities specifically named in this section.

The study was initially funded by the House Appropriations Committee in its Report No. 97-177, 97th Congress, 1st Session (page 23).

Prior Reports

1.7. The following related reports, prepared by the Army Corps, contain significant data on littoral zone sediments.

Title	Date
Beach Erosion Study, Capitola Santa Cruz Co., California U.S. Army Engineer District, San Francisco.	November 1969
Cooperative Beach Erosion Study Point St. George to Point Lobos, Ca U.S. Army Engineer District, San Francisco.	November 1975
Reconnaissance Report on Coastal Erosion Ft. Ord, California Miscellaneous Paper CERC-83-10.	December 1983

2. LITTORAL-ZONE RESOURCES

2.1. The littoral zone is an area where waves, currents, and winds interact with the land and its sediments; the intensity of these physical processes or driving forces determines the configuration of the coast and composition of its beaches (Inman and Brush, 1973). Bays, being indented regions along a coast, are affected by a variety of physical processes, and, accordingly, the shape of the shore and the nature of the coastal sediments varies from place to place within them. This chapter summarizes the published data pertaining to the littoral zone of Monterey Bay. Topics covered include the geomorphology of the coastal zone, the sediment distribution within the bay, and the physical processes that shape the littoral zone and control the observed sediment distributions. Each major section starts with a general discussion of the relevant principles and ends with a summary of the available data for Monterey Bay. The *Morphodynamic Processes* Chapter explains how all these factors–geomorphology, composition, and processes–interact within Monterey Bay.

2.2. Komar (1976, p. 11-13) defined the littoral zone to be a region of unconsolidated sediment that starts at the seaward edge of some geomorphic feature–sea cliff, dune field, or other feature–or at the point where permanent vegetation is established and extends to an offshore depth at which wave activity is no longer generally important in moving sediment. For the purpose of this report, a depth of about 20 m will be used to designate the outer edge of the littoral zone within Monterey Bay. However, that depth may be too shallow in some cases; for example, Yancey (1968) believed that wave processes were responsible for the observed systematic decrease in grain size from the surf zone to the edge of the continental shelf, which is in a water depth of over 100 m.

Littoral-Zone Geomorphology

2.3. The littoral zone comprises a backshore, foreshore, inshore, and offshore. The backshore, which is the area landward of the foreshore, and the foreshore, which extends from the berm crest (or point of highest runup at high tide) to the low-water mark of the backrush at low tide, make up the beach. The inshore spans the area between the seaward edge of the foreshore and the seaward edge of the breakers; the offshore extends from beyond the breaker zone to the outer limit of the littoral zone (and beyond). Figure 2-1 shows a generalized cross-section or profile of the littoral zone; not all of the features shown on that profile may be present at any given time. For example, the summer or swell profile is characterized by a wide berm and smooth, barless nearshore profile; the winter or storm profile has almost no berm and a series of shore-parallel bars in the nearshore (fig. 2-2). In general, a profile depends upon the size and amount of available sediment and the local wave climate (Wiegel, 1964).

2.4. Inman (1971) describes beaches as long rivers of sand; waves and currents drive the sand that has been transported to the coast by streams or eroded from coastal cliffs and dunes. Inman also states that beach geometry depends on the type of coast: long, straight beaches are typical of low, sandy coasts, and shorter crescent-shaped beaches and small pocket beaches are more common along mountainous coastlines. On a smaller scale, sections of a long, straight beach may have longshore topographic fluctuations. The scale of the fluctuations ranges from a few tens of meters (beach cusps) to more than 1000 m (protuberances–sandwaves, shoreline rhythms, giant cusps, nesses–King, 1982, p. 688).

2.5. Man-made structures can alter the natural geomorphology of the coastal zone. A

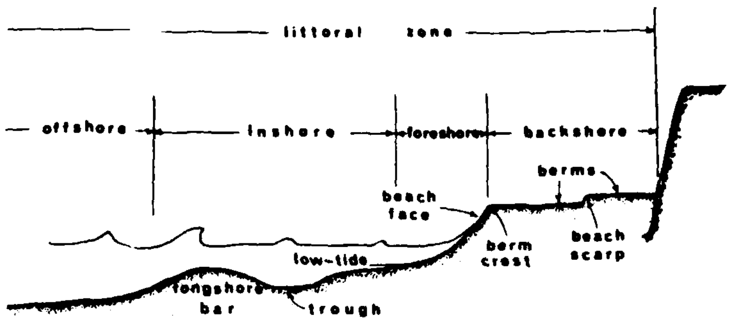

Figure 2-1. Sketch showing the terminology used to describe a beach in profile [*from* Komar, 1976, p. 12].

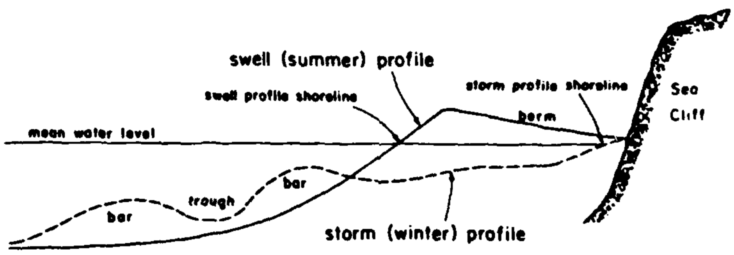

Figure 2-2. Comparison of a swell (or summer) profile with a storm (or winter) profile. The swell profile has a pronounced berm and no nearshore bars, and the storm profile has little-or-no berm and one-or-more bars [*from* Komar, 1976, p. 288].

breakwater, jetty, or groin restricts the longshore movement of sand, often causing large-scale accretion updrift of the structure and erosion downdrift. Piers can produce a similar effect if not properly designed. Seawalls and revetments protect the land immediately behind them, but after the walls are built, increased wave turbulence causes the natural beach to disappear (Inman, 1976, p. 30). Also, adjacent, unprotected areas continue to erode, often at increased rates.

GEOMORPHIC OVERVIEW OF MONTEREY BAY

2.6. Monterey Bay is a wide, westward opening, semicircular embayment located on the central California coast. The bay is about 40 km long in a north-south direction and extends to the edge of the continental shelf, which is less than 20 km west of the bay's eastern shore. Shoreline types include narrow beaches adjacent to coastal terraces, long stretches of wide, sandy beaches, and rocky areas with pocket beaches. Plate 1 shows the topography of the Monterey Bay area and the location of many of the bay's beaches and other coastal features.

2.7. Moving clockwise from Point Santa Cruz around Monterey Bay, the coastline first runs east for about 10 km to Capitola, then south for about 50 km to Monterey, and finally northwest for about 6 km to Point Piños. Habel and Armstrong (1978, p. 43) divided the shoreline of the bay into three geomorphic categories:

1. The northern shoreline consists of eroding bluffs and cliffs with pocket beaches and a few noneroding headlands. Santa Cruz Harbor is located in the western half of this area, and the San Lorenzo River and Soquel Creek enter the bay in this area.
2. The eastern shoreline is sandy over its entire length and has adjusted to conform closely with the crests of incoming waves. Though the shoreline here is continuous, it has been divided arbitrarily into several beaches (Plate 1). The entrance to Moss Landing Harbor breaks the shoreline in the center, the Pajaro River enters the bay north of Moss Landing, and the Salinas River enters to the south. In the recent past, the northern beaches have been relatively stable while the southern beaches have undergone modest to severe erosion. Weber (oral comm., 1985) suggests that the northern beaches may start to erode because of the loss of an upcoast sand source (discussed in the *Coastal-Cliff Resources* and *Morphodynamic Processes* Chapters).
3. The shoreline between Monterey and Point Piños is rugged with pocket beaches. Monterey Harbor is located at the boundary between this section of the shoreline and the previous one.

2.8. Using U. S. Coast and Geodetic Survey charts from 1851-54, 1910, and 1933 surveys and a U. S. Army Corps of Engineers chart from a 1948 survey, the U. S. Army Corps of Engineers (1958) determined shoreline changes between Año Nuevo and Point Piños. They found that the shoreline along much of the bay had prograded, but that it had retrograded extensively in the northern portion of the bay between the San Lorenzo River and a point 1.6 km east of Soquel Creek and along a 3.2-km reach north of the Pajaro River. Based on bluff retreat, the north coast of the bay was retreating an average of 0.3 m/yr (also, see the Chapter on *Coastal Cliffs*). The shoreline prograded the most at the mouth of the Salinas River.

2.9. More recently, Arnal and others (1973), Combellick and Osborne (1977), Dorman (1968), the U. S. Army Beach Erosion Board (in Hart, 1966, p. 86), and Welday (1972) have all reported that parts of the bay south of the Salinas River are actively eroding. Table 2-1, from Allayaud (1978), summarizes the south bay erosion rates reported in four studies.

Investigator	Rate (m/yr)	Period	Location
Dorman	1.2	1945-68	Seaside to 914 m south of the Salinas River
Arnal and others	0.5-0.6 0.9-1.5 1.5	1919-23 1944-61 1961-67	southern Monterey Bay Sand City area Sand City area
Welday	0.4 0.4-0.8	1932-70 1932-70	Marina area Sand City area
Thompson	0.2-0.7 0.4-1.0	1864-1977 1932-70	Monterey Bay Sand City

Table 2-1. Shoreline erosion rates for Monterey Bay, especially the southern half of the eastern shore [*adapted from* Allayaud, 1978]. Thompson's data was contained in a 1977 report to a sand mining company; the 1977 date on the first line of his data is assumed from the entry '1864-77'.

2.10. The predominant offshore feature within the bay is Monterey Submarine Canyon, which cuts across the shelf in the center of the bay. The canyon head has three branches, and all of those extend into the littoral zone at Moss Landing (fig. 2-3). The north branch starts directly offshore of the entrance channel that leads into Moss Landing Harbor, the south branch starts just seaward of a pier at a depth of 18 m, and the middle one lies in between (Shepard and Dill, 1966). The canyon's 500-m depth contour is less than 10 km from the beach (plate 1). Water depths in the canyon constantly change as sediments are deposited in the head and later flushed down the canyon's axis into deeper water. Shepard (1963) compared two sets of soundings in the head of Monterey Canyon that were taken 14 years apart. He found that the canyon head had not filled even though there was active sedimentation there. He reasoned that the sediment was removed from the head by slumping; the high slopes in the canyon head encourage slumping of the sediment, which then form turbidity currents that move sand into deeper.

2.11. Offshore, they found general deepening in the area between the Pajaro River and Monterey Submarine Canyon, shoaling between the canyon and the mouth of the Salinas River, and deepening in the area between the Salinas River and Monterey. Within the canyon, they noted both erosion and accretion. Between the 1933 and 1948 surveys, the canyon head accreted and the offshore part to the 37-m contour eroded.

COASTAL STRUCTURES

Shore-Normal Structures

2.12. Within Monterey Bay, the littoral zone has been or could be altered by several structures that extend into the nearshore. These include:

- Jetties at the entrances to Santa Cruz and Moss Landing Harbors.
- Two breakwaters protecting Monterey Harbor.
- Piers at Santa Cruz, Capitola, Seacliff, and Moss Landing.
- A groin on the east side of Capitola Beach.

There is a pier within Monterey Harbor, but it does not influence littoral processes outside the

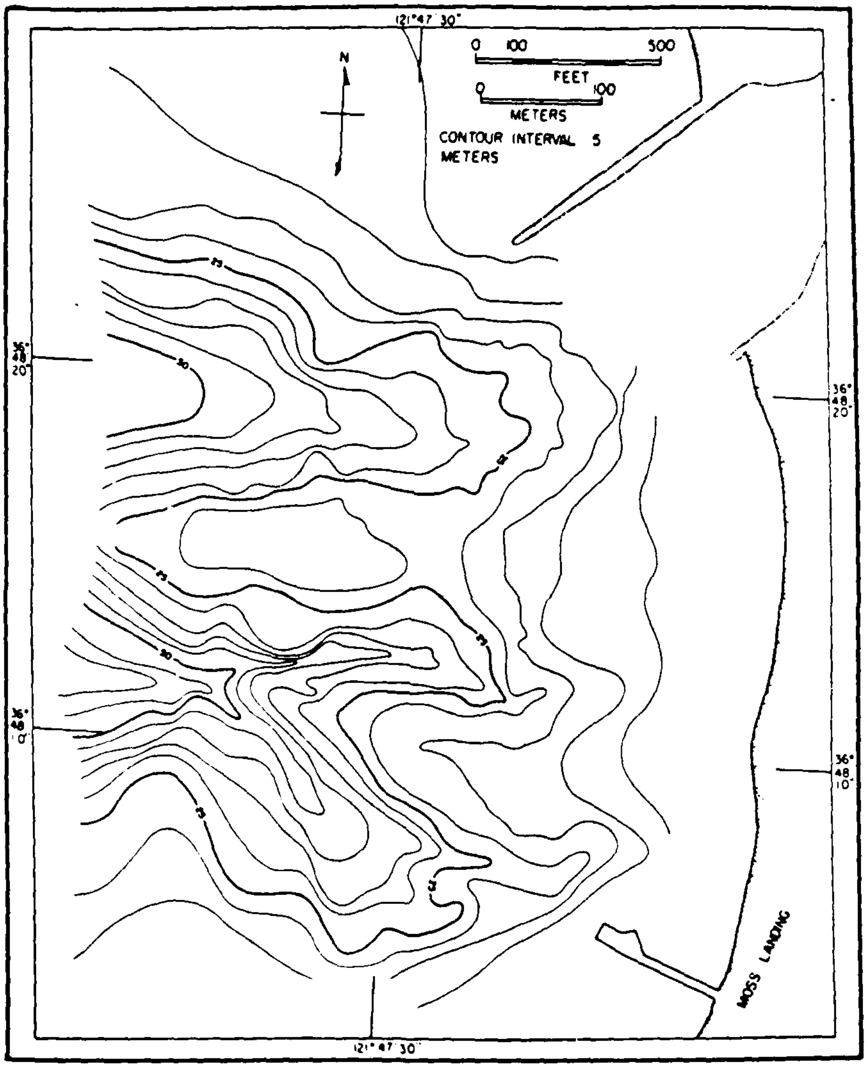

Figure 2-3. Bathymetry of the head of Monterey Submarine Canyon, just offshore from Moss Landing [*from* Shepard and Dill, 1966, p. 83].

harbor. Also, there are several large sewage drains that, in some places, now extend into the surf zone because of extensive shoreline retreat in their areas.

2.13. **Santa Cruz Harbor** was constructed in the early 1960s as part of a project to convert Woods Lagoon, which is about 1 km east of the mouth of the San Lorenzo River, into a small-boat basin. As designed, the harbor consisted of two rubble-mound jetties, 360 m long on the west and 243 m long on the east; a 381-m long entrance channel that varied in depth from 6 m to 4.5 m; a 340-m long inner channel, which decreased in depth from 4.5 m to 3 m; and a turning basin. In case the jetties caused downdrift beach retreat, a sand-bypassing plan was developed (Seymour and others, 1980). The harbor was built, but the sand-bypassing plan was not implemented. As a result, Seabright Beach, which abuts the west jetty, widened by more than twelve times to about 100 m, and Capitola Beach, about 5 km east of the harbor, soon lost over 90% of its sand, becoming only a few meters wide (Griggs and Johnson, 1976). Eventually, the City of Capitola built a 75-m long groin at the eastern end of Capitola Beach to trap sand. The harbor entrance shoals constantly, often to the extent that it is impassable. From 1965 to 1974, 570,000 m^3 of sand were dredged from the harbor entrance with the yearly average being 75,000 m^3/yr since 1970 when Seabright Beach stabilized (Griggs and Johnson, 1976).

2.14. **Moss Landing Harbor** was built in 1946-1949 to provide a small-boat harbor at Elkhorn Slough, in the center of Monterey Bay. Included in the project were the construction of two wooden-piling jetties, an entrance channel, and a lagoon channel (Wong, 1970). The north jetty, which was to be about 275-m long, and the south one, about 190-m long, were to be spaced about 182-m apart, and the entrance channel was to be dredged to about 4.5 m. Storms damaged the jetties during construction, and eventually rubble-mound jetties were built in the place of the wooden ones. In 1966-1967 the jetties were extended into the lagoon to eliminate erosion of the lagoonal shorelines next to the jetties. Wong (1970) reported that there had been some shoaling in the entrance channel that required dredging. The shorelines on both sides of the entrance have fluctuated, but in 1970 appeared to be close to their 1940 locations. After jetty construction, the head of the canyon appeared to have accreted (Wong, 1970); however, the end of the north jetty has slumped into the canyon at least once.

Shore-Parallel Structures

2.15. Seawalls are common in parts of Monterey Bay, especially between Santa Cruz and Rio Del Mar. They are used to protect sea cliffs and homes built immediately behind narrow beaches that are attacked during intense winter storms. Though less common in the south bay because of fewer coastal homes, shoreline retreat has reached the point where buildings are being threatened during extremely stormy seasons. For example, Stilwell Hall, on the Fort Ord grounds was built a few hundred meters inland; now the west corner of the building is at the edge of the cliff, and the cliff face is protected by rock.

BEACH SHAPE

Profiles

2.16. As described above, changes in wave climate produce changes in beach morphology. Though the formation or disappearance of beach cusps and larger rhythmic features is sometimes dramatic, the origin of those features is still not well understood (Spasari, 1982). Profile changes, on the other hand, are better understood, though Sallenger and others (in press) suggest that the response of the littoral zone profile is more complex than suggested by the swell-storm model. Also, a profile is only an instantaneous picture of the beach, and it is difficult to determine if that profile represents a long-term condition or a recent change in response to changing wave conditions (U. S. Army Coastal Engineering Research Center, 1977). Profile data for selected Monterey Bay beaches are available from several sources. Those profiles show some configurations taken by the bay's beaches; however, other shapes will occur in response to different wave climates. Wave data were not collected in conjunction with the beach surveys, so that it is not possible to say accurately what wave conditions produced the measured profiles.

2.17. Bascom (1951) surveyed four Monterey Bay beaches as part of a four-year study of 40 Pacific Coast beaches. He, and later, Wiegel (1964) used that data to determine the relation between beach slope and the "reference point" grain size, where the reference point is the part of the beach face subject to wave action at mid-tide level (Bascom, 1951). As shown in figure 2.4, they found that the smaller the grain size, the flatter the beach-face slope. Furthermore, data for exposed beaches, somewhat-protected beaches, and protected beaches plot on separate curves; for a given grain size, slope is directly proportional to the extent that a beach is protected. Table 2-2 lists the slope values for Monterey Bay beaches named in figure 2.4. Note that these are average values for the beaches; the actual slope of any beach varies with wave climate such that a beach has a smaller slope when it is retreating than when building out (Bascom, 1980, p.261).

Beach	Beach Face Slope	Median Grain Size (mm)
Seabright	.084	.39
Moss Landing South	.068	.25
	.069	.30
Fort Ord, 1	.089	.45
	.089	.50
	.089	.55
Fort Ord, 2	.091	.54
	.120	.53
Fort Ord, 3	.120	.53
	.120	.61
	.112	.61
	.140	.63
	.120	.66
	.120	.73
Fort Ord, 4	.130	.71
Monterey	.025	.23

Table 2-2. *Relationship between beach-face slope and median grain size for selected Monterey Beaches* [*adapted from* Wiegel, 1964).

2.18. The U. S. Army Corps of Engineers (1975) surveyed several beaches between Point St. George and Point Lobos. Their surveys of Manresa State Beach (fig. 2-5) and the beach at the mouth of the Salinas River (fig. 2-6) were conducted during both the spring and fall of 1971. At Manresa State Beach, surveys ran along two ranges that started on a bluff behind the beach and ended at MLLW (Mean Lower Low Water, the tidal d tum for this section of coast). On the plotted profiles, beach-face slopes measured at MSL (Mean Sea Level; this elevation was used to

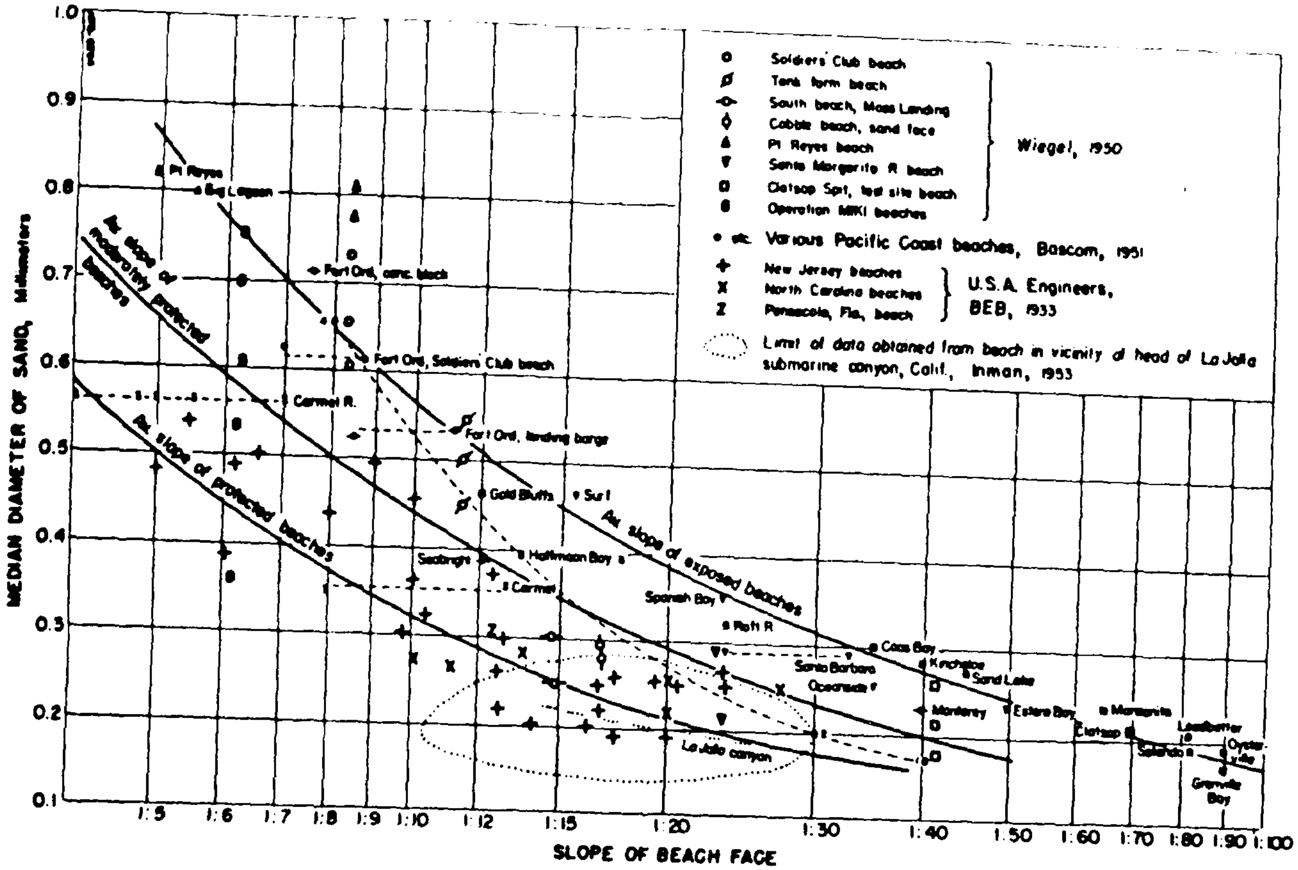

Figure 2-4. Beach-face slope as a function of median grain size of the sand at the reference point [from Wiegel, 1964, p. 359].

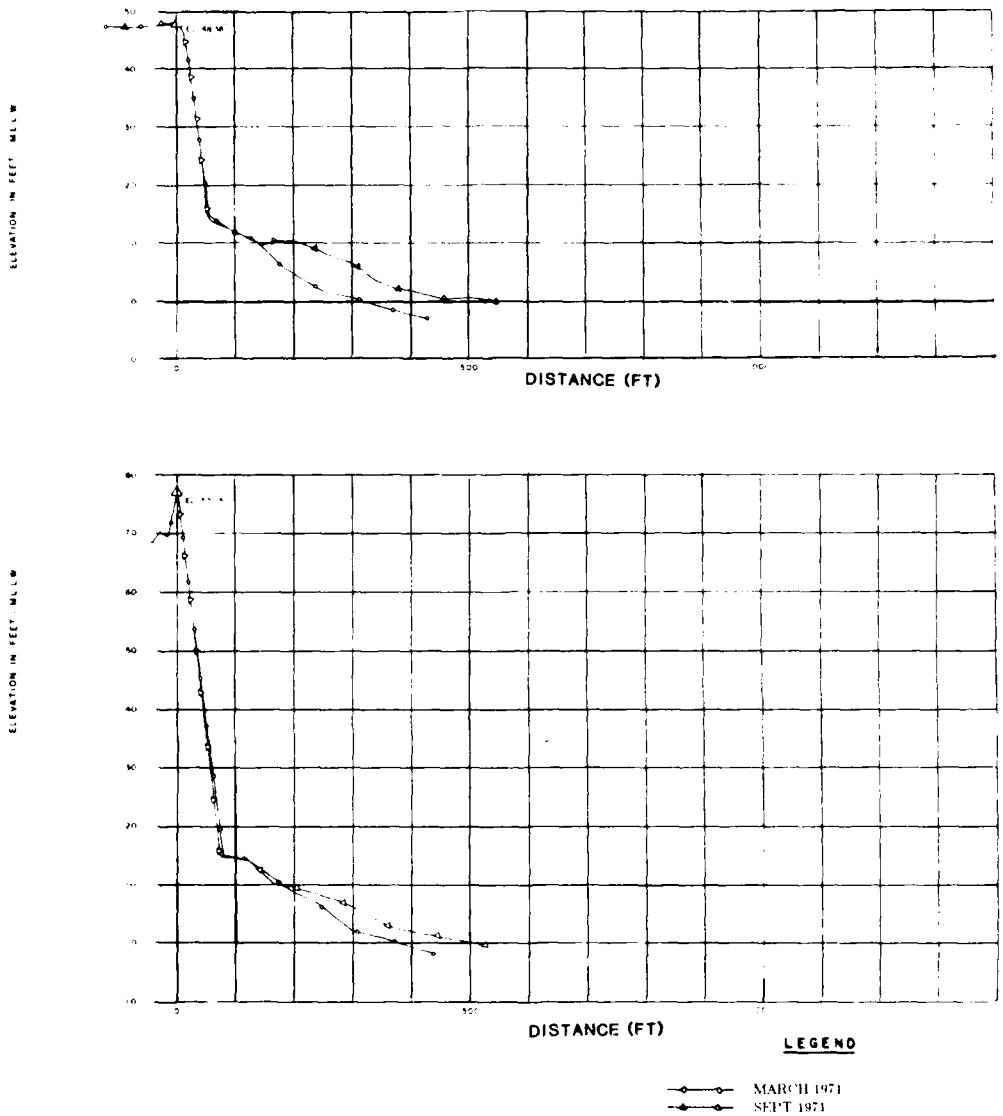

Figure 2-5. Spring and fall (1971) profiles of Manresa State Beach [*from* U. S. Army Corps of Engineers, 1975]. Elevations and distances are in feet.

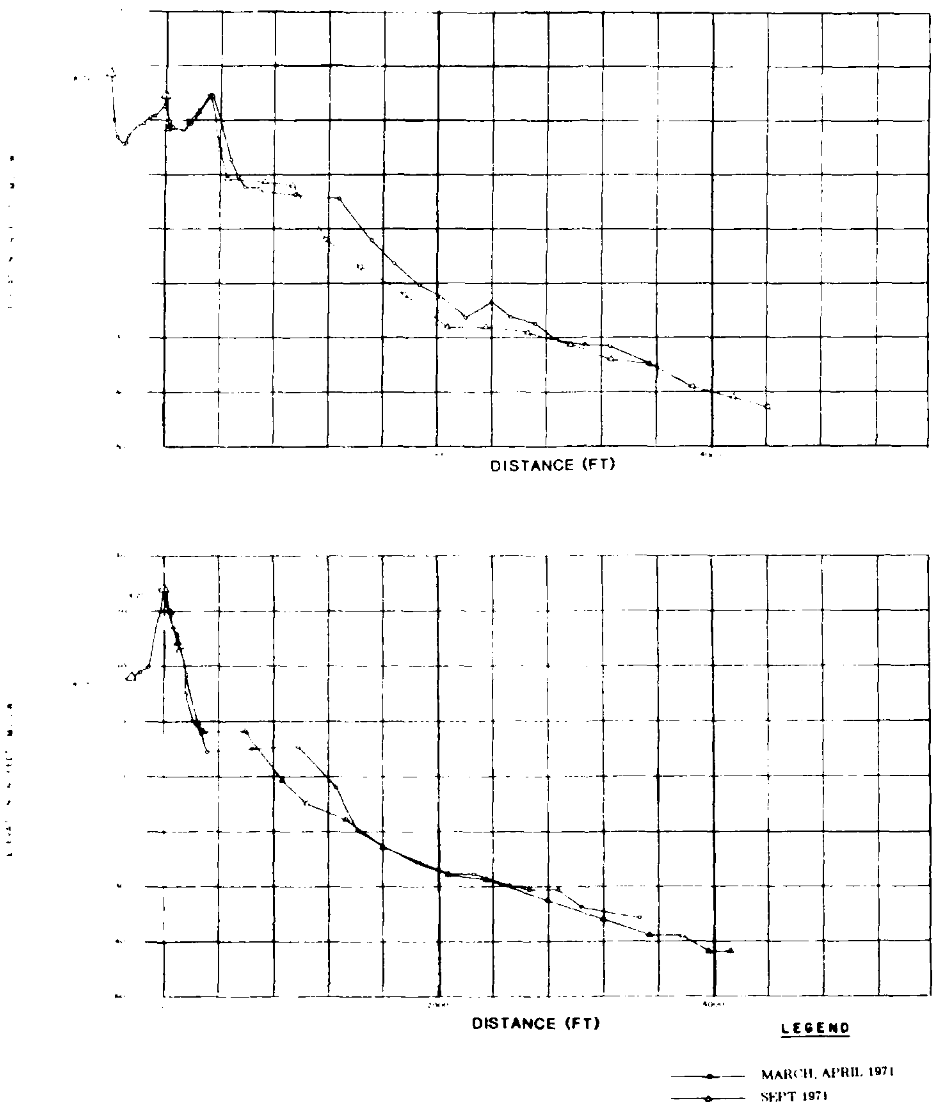

Figure 2-6. Spring and fall (1971) profiles of the beach at the mouth of the Salinas River [*from* U. S. Army Corps of Engineers, 1975]. Elevations and distances are in feet.

approximate the reference point) were 0.062 and 0.057 in the spring and 0.045 and 0.047 in the fall. They also established a range on either side of the mouth of the Salinas River. These started on the back beach and ended in a water depth of about 12 m. Slopes were 0.079 and 0.102 in the spring and 0.090 and 0.087 in the fall.

2.19. In February 1983, Dingler and others (1985) began surveying nine beaches on the eastern shore of Monterey Bay; twelve sets of onshore profiles were collected. Table 2-3 lists the nine beaches, and table 2-4 gives the survey dates.

Line No.	Beach	Line No.	Beach
1	Seacliff State Beach	6	Salinas River Mouth
2	Manresa State Beach	7	Fort Ord Beach
3	Sunset State Beach	8	Sand City Beach
4	Moss Landing State Beach	9	Del Monte Beach
5	Salinas River State Beach		

Table 2-3. Monterey Bay Beaches Surveyed Between February, 1983 and January, 1985 [*from* Dingler and others, 1985].

No.	Date	Beaches Surveyed	No.	Date	Beaches Surveyed
1	3, 4 Feb. 83	1-9	7	14, 15 July 83	1-9
2	22-24 Feb. 83	1-9	8	13,14 Sep. 83	1-9
3	7, 8 Mar. 83	1-9	9	14 Nov. 83	2-5,7
4	6, 7 Apr. 83	1-9	10	13, 14 Feb. 84	1-9
5	5, 6 May 83	1-9	11	27, 29 Sep. 84	1-9
6	2, 3 June 83	1-9	12	16, 17 Jan. 85	1-9

Table 2-4. Dates for the surveys listed in table 2-2. [*from* Dingler and others 1985].

These beaches were surveyed to monitor erosion during and recovery after the winter of 1982-83. Profiles extended from a reference marker behind the beach to wading depth. After visually inspecting the profiles to determine the nature of the changes to the beaches, an empirical eigenfunction analytical procedure was used to quantify those changes. Because this technique requires survey lines of equal length, only the part of each beach spanned by the shortest profile was analyzed. Figure 2-7 shows the results from the empirical eigenfunction analysis of the nine beaches. The first temporal eigenfunction, which is a measure of the volume per unit width of beach, differs in detail for the nine beaches, though most of the beaches show a similar pattern with low values early in the study and higher values at the end.

2.20. Dingler and others (1985) present the complete set of profiles for Manresa State Beach and the beach at Fort Ord just south of Stilwell Hall (figs. 2-8 and 2-9). At Manresa State Beach, beach-face slopes ranged from 0.04 to 0.14 with an average of 0.09. At Fort Ord, they ranged from 0.13 to 0.20 with an average of 0.16, which is higher than the averages given by Bascom (1951) or Wiegel (1964). The difference may not be real because slopes were measured off the plotted profiles in Dingler and others without accurate knowledge of the location of the reference point. If the slopes were measured above the reference point, they could be higher than those obtained at the reference point (Bascom, 1951). Nevertheless, the two sets of profiles

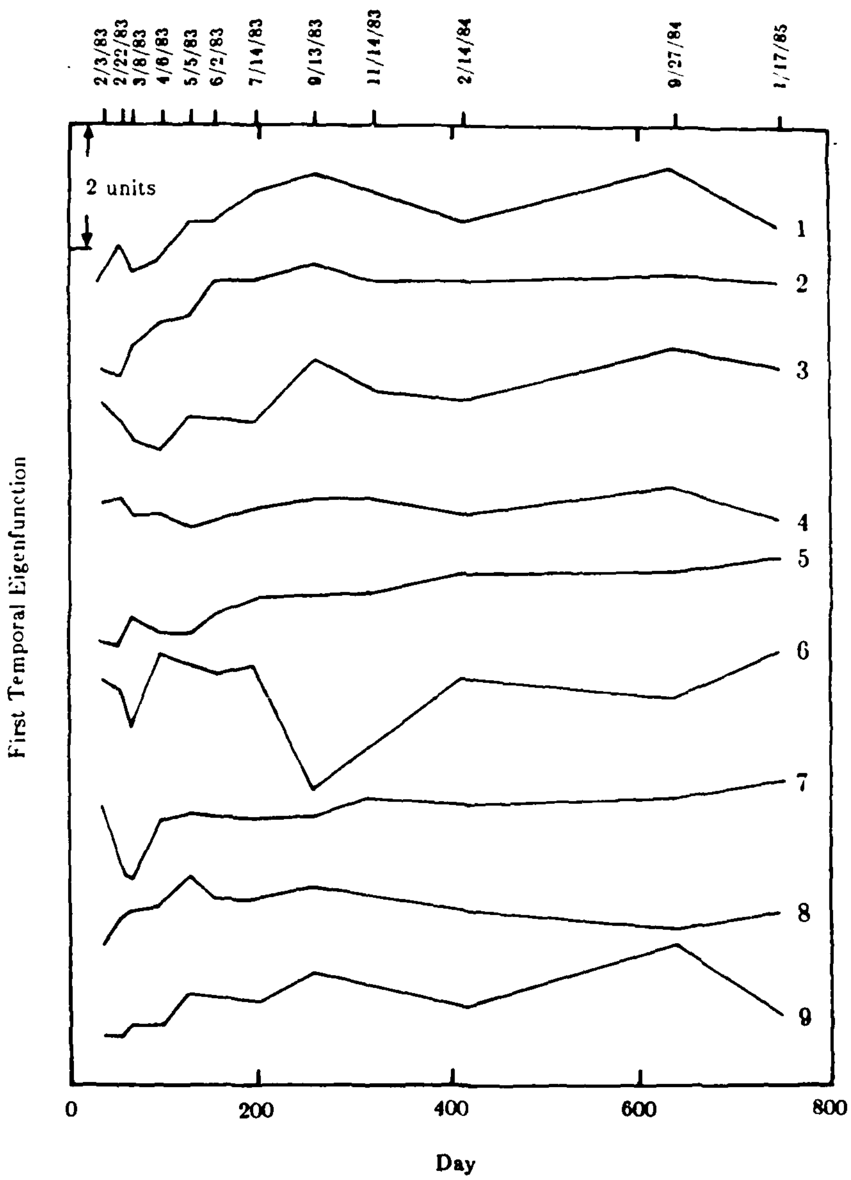

Figure 2-7. The first temporal empirical eigenfunction for nine beaches along the eastern shore of Monterey Bay. Curves have been offset vertically for clarity. A change of one eigenfunction unit is roughly equal to a volumetric change of 50 m^2 per meter of beach [*from* Dingler and others, 1985].

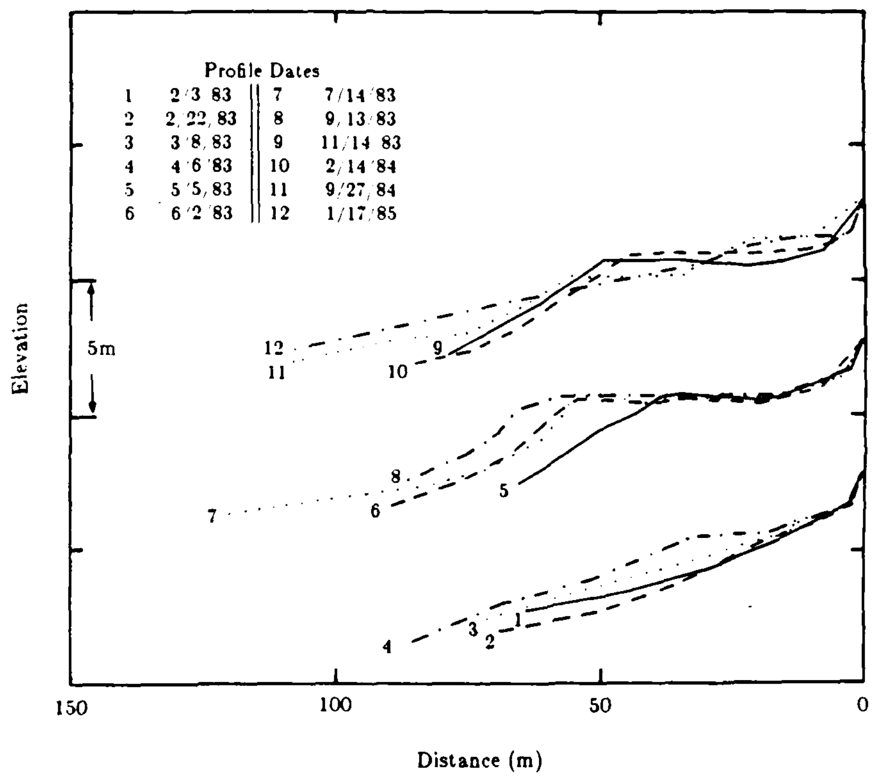

Figure 2-8. Main-line profiles taken at Manresa State Beach. The profiles have been split into three groups for clarity. The profiles are numbered in sequence at the offshore end of each [*from* Dingler and others, 1985].

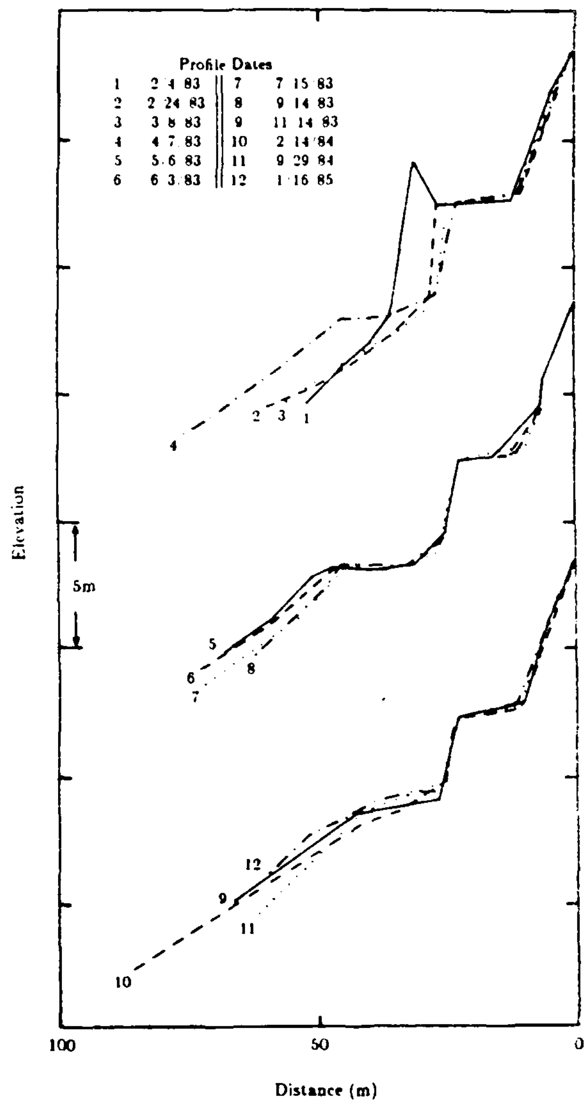

Figure 2-9. Main-line profiles taken at Fort Ord Beach. The profiles have been split into three groups for clarity. The profiles are numbered in sequence at the offshore end of each. The profiles start on the seaward flank of a large coastal dune, level off on the top of the bluff, and then drop to the beach. On the first profile, the peak on the edge of the bluff was a pile of sand that had been presumably placed there by Fort Ord personnel [*from* Dingler and others, 1985].

clearly show that the beach at Fort Ord has a greater average slope than the one at Manresa State Beach.

Berm Heights

2.21. Using a laboratory wave channel, Bagnold (1940) showed that the maximum height of the berm above sea level should be 1.3 times the deep-water height of the waves that formed them, irrespective of beach-face slope and grain size. Bascom (1980, p. 261) said that this relation appears to apply to ocean waves if the berm-height calculated by Bagnold's relation is multiplied by the wave-refraction coefficient for the beach of interest, though tides could blur the relationship. For example, he stated that the berm was at least 5 m above low water at Fort Ord and less than 2 m at Monterey. Berm heights are less variable in the northern part of Monterey Bay. Profiles show that the berm was about 3 m above low water at Manresa State Beach (U. S. Army Corps of Engineers, 1975); and about 3.5 m above low water at Santa Cruz and Twin Lakes Beaches (U. S. Army Corps of Engineers, 1958).

Longshore Variability

2.22. Beach morphology is often highly variable alongshore, even under "equilibrium conditions". This variability produces a three dimensionality on the beach that is often missed during surveys along standard two-dimensional profile lines. The resulting profiles show changes that are interpreted to indicate erosion or accretion of the entire beach, whereas the changes are really do to shifts in the features that produced the three-dimensionality (Sonu, 1973). Figure 2-10 shows two sets of four beach profiles taken over a ten-week period (7 June to 1 September 1981) at Ft. Ord (Laband, 1984). Although these profile lines were only 60-m apart, they exhibit two different sequences of foreshore change. Profile line 1 records about 20 m of accretion from 17 June to 7 July, followed by about 15 m of erosion from 7 July to 1 September. Profile line 2, however, records about 8 m of erosion from 17 June to 7 July, followed by about 20 m of accretion from 7 July to 1 September.

2.23. The opposing histories of these two profile lines are the result of the development of a highly rhythmic, cuspate foreshore, which the two-dimensional profile lines fail to represent. Figures 2-11 and 2-12 are foreshore topographic maps, made at the same time and location as the profile lines (Laband, 1984). Profile-line locations are marked on each map. On 7 July, the entire foreshore (MSL to +4.0 m) morphology was highly cuspate (fig. 2-11). This giant cuspate feature, which had a wavelength of 170 m, was repeated in the longshore direction, developing a rhythmic longshore pattern. By 20 August, this same foreshore area was extremely linear at MSL, with shorter wavelength (25 m) cusps on the upper foreshore (fig. 2-12). The Monterey Bay shoreline commonly develops a highly-rhythmic foreshore. Therefore, profile changes may not represent a net loss or gain of sand to the beach, but only longshore variability that changes with time.

Sediment Texture and Composition

2.24. Studies of the sediments of Monterey Bay have delineated several sedimentary provinces within the bay. Attempts to define the provenance of the littoral-zone sands from the heavy-mineral constituents have met with some success, though similarity amongst the basement rocks of the various drainage basins makes the exact determination of ultimate provenance essentially impossible in many cases. The bay's sediments have been analyzed for mineral composition and texture, including grain size and its related parameters (sorting, skewness, kurtosis) and surface

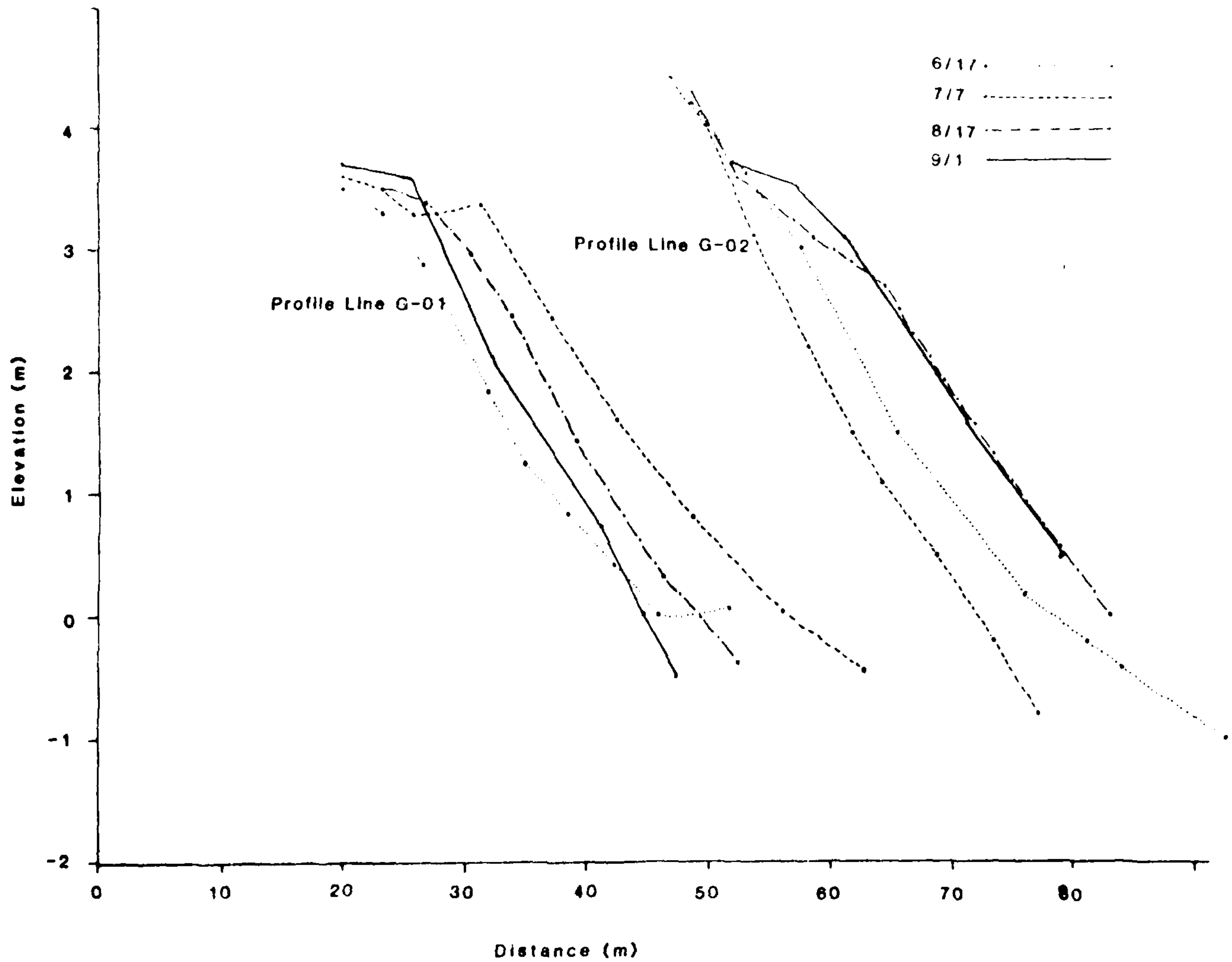

Figure 2-10. Foreshore profile lines spaced 60 m apart at Ft Ord [*from* Laband, 1984]

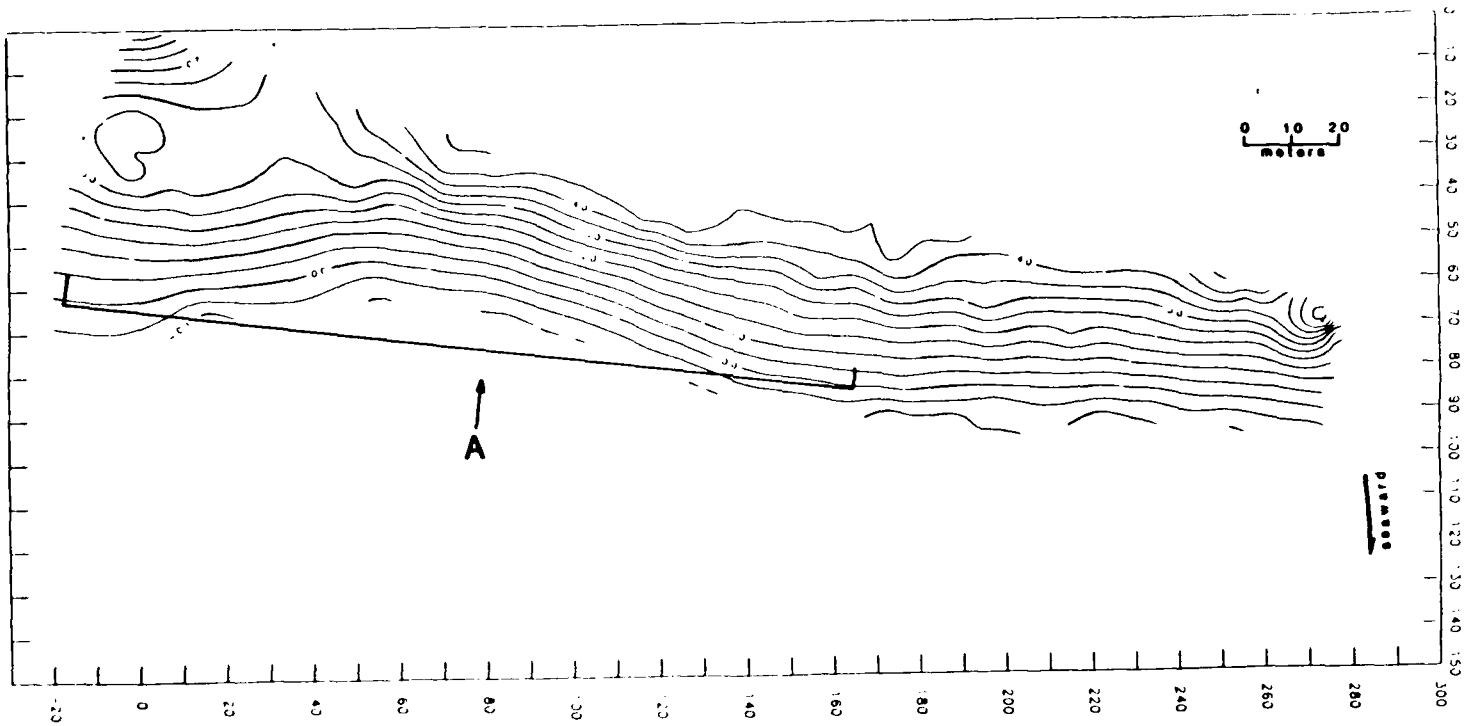

Figure 2-11 Foreshore topographic map, Ft. Ord (A) 170 m long giant cusp with a 14 m cusp height at MSL [*from* Laband, 1984]

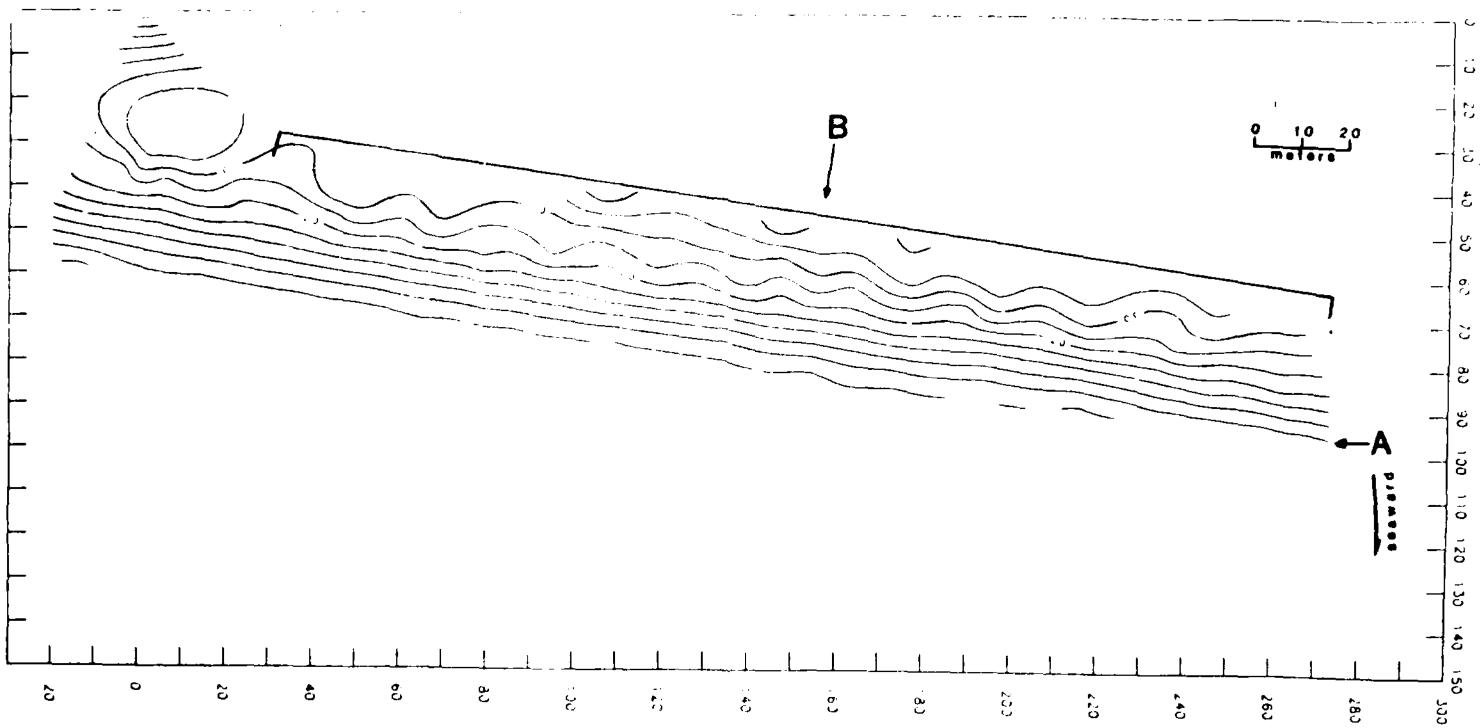

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Figure 2-12 Foreshore topographic map, Ft. Ord (A) extremely linear shoreline at MSL, (B) 25 m long cusps on the upper foreshore [*from* Laband, 1984] features. Because it most clearly shows major trends, the textural parameter emphasized in this section is grain size; other parameters will be touched upon in the section on Mining.

GRAIN-SIZE DISTRIBUTION

2.25. Galliher (1932) and Wolf (1970) described the general grain-size distribution within Monterey Bay. Their data (figs. 2-13 and 2-14) show a grain-size decrease in the offshore direction, and a distribution of size classes* that was roughly parallel to the isobaths

2.26. Yancey (1968), who sampled throughout the bay and its feeder streams north of Fort Ord and on the beach south of Fort Ord, also found that grain size decreased from the beach to a depth of about 100 m; however, he found an increase in grain size on the edge of the shelf. Figure 2-15 shows sample locations and median grain sizes for the sand fraction of those samples. He concluded that the grain-size distribution within the bay could be divided into three categories:

1. Coarse-grained relict sediment along the shelf edge.
2. Fine-grained modern sediment on the mid-shelf.
3. Medium-to-coarse modern-to-relict nearshore sands.

Because of their general fining-seaward nature, Yancey felt that the sediments in categories 2 and 3 were in adjustment with modern processes. Sorting** was best on the mid-shelf and got poorer both onshore and offshore, except for a slight improvement at the beach. This zone of lowest sorting values corresponded to the zone of least median sand size. Figure 2-16 shows the distribution of the phi sorting coefficient for the sand fraction in Monterey Bay. In the northeastern corner the sands tended to be finer than their counterparts at a similar depth elsewhere in the bay, and sorting was correspondingly higher in that corner.

2.27. Dorman (1968) limited his study to the beaches and bay bottom in a 40 km^2 area of southern Monterey Bay between the northern boundary of Fort Ord and the Monterey

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*For sand-sized material, the classes used in this report are:

Range (ϕ)	Range (mm)	Wentworth Class
4 - 3	0.0625 - 0.125	very-fine sand
3 - 2	0.125 - 0.250	fine sand
2 - 1	0.250 - 0.500	medium sand
1 - 0	0.500 - 1.000	coarse sand
0 - -1	1.000 - 2.000	very-coarse sand

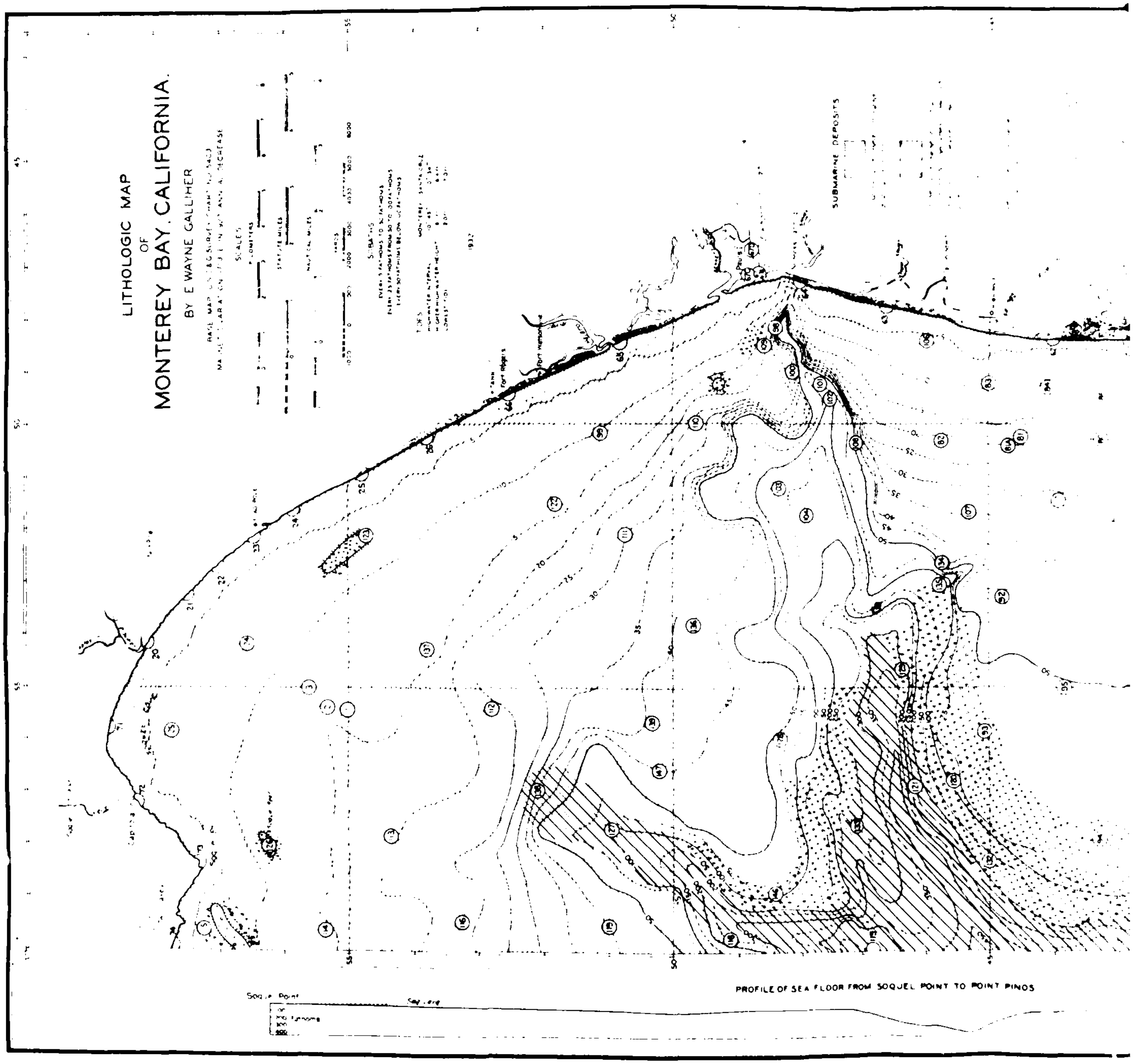
Where grain size in phi units (ϕ) is related to grain size in millimeters by the relation

$$D_{mm} = (1/2)^{\phi}.$$

See also U. S. Army Corps of Engineers (1984, p. 3-4).

**Sorting is a measure of the range of grain sizes present in a sample. The phi sorting coefficient equals one half the difference between the third and first quartile fractions. The scale used by Yancey (1968) is:

Sorting Coefficient (ϕ)	Class
0.0 - 0.23	very-well sorted
0.23 - 0.26	well sorted
0.26 - 0.425	moderately-well sorted
0.425 - 0.91	moderately sorted
0.91 - 1.47	poorly sorted
>1.47	extremely-poorly sorted


LITHOLOGIC MAP
OF
MONTEREY BAY, CALIFORNIA.
BY E. WAYNE GALLIHER
SCALES
SUBMARINE DEPOSITS
PROFILE OF SEA FLOOR FROM SOQUEL POINT TO POINT PINOS
Soquel Point

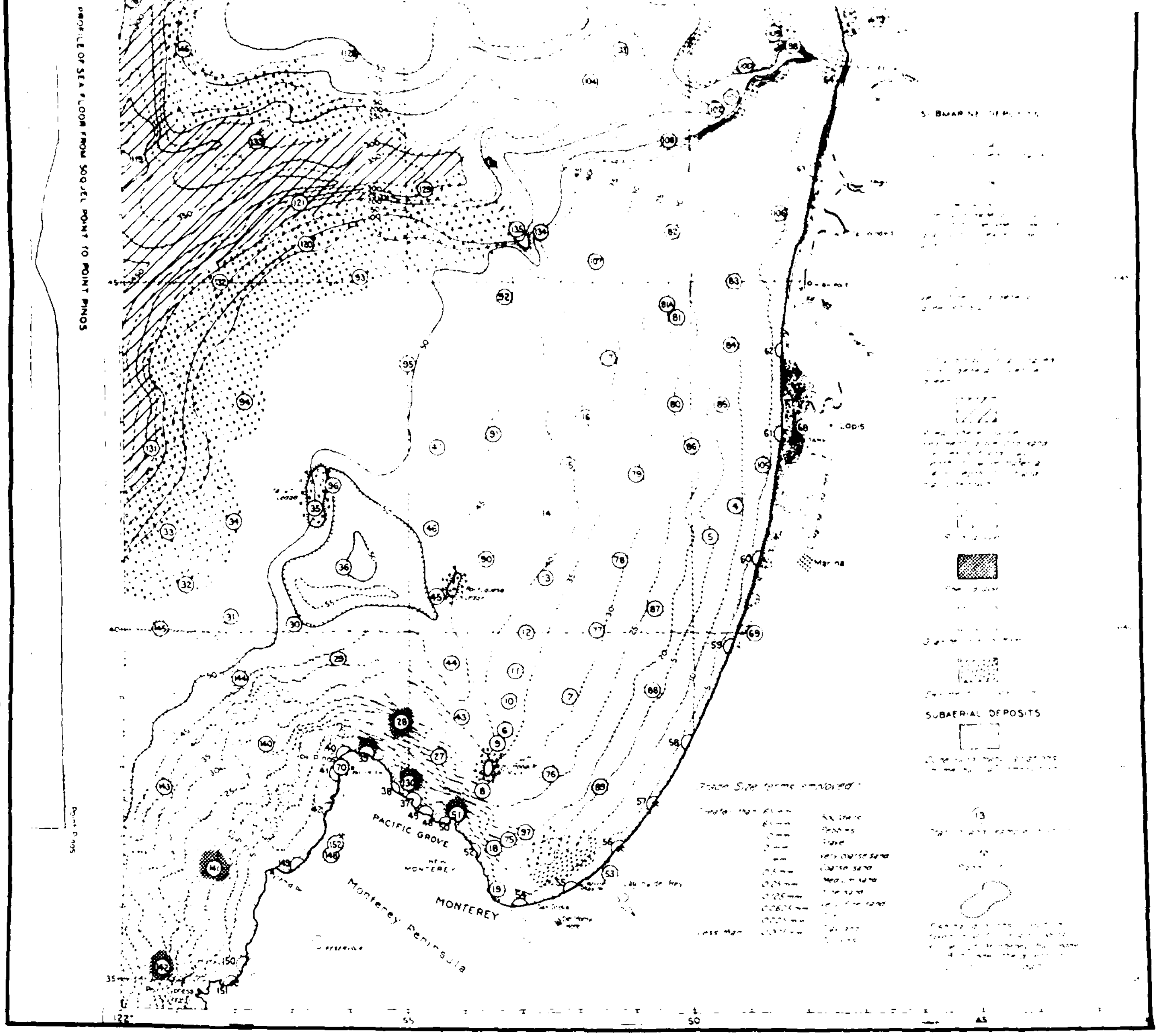


Figure 2-13 Lithologic map of Monterey Bay (from Galliher, 1932)

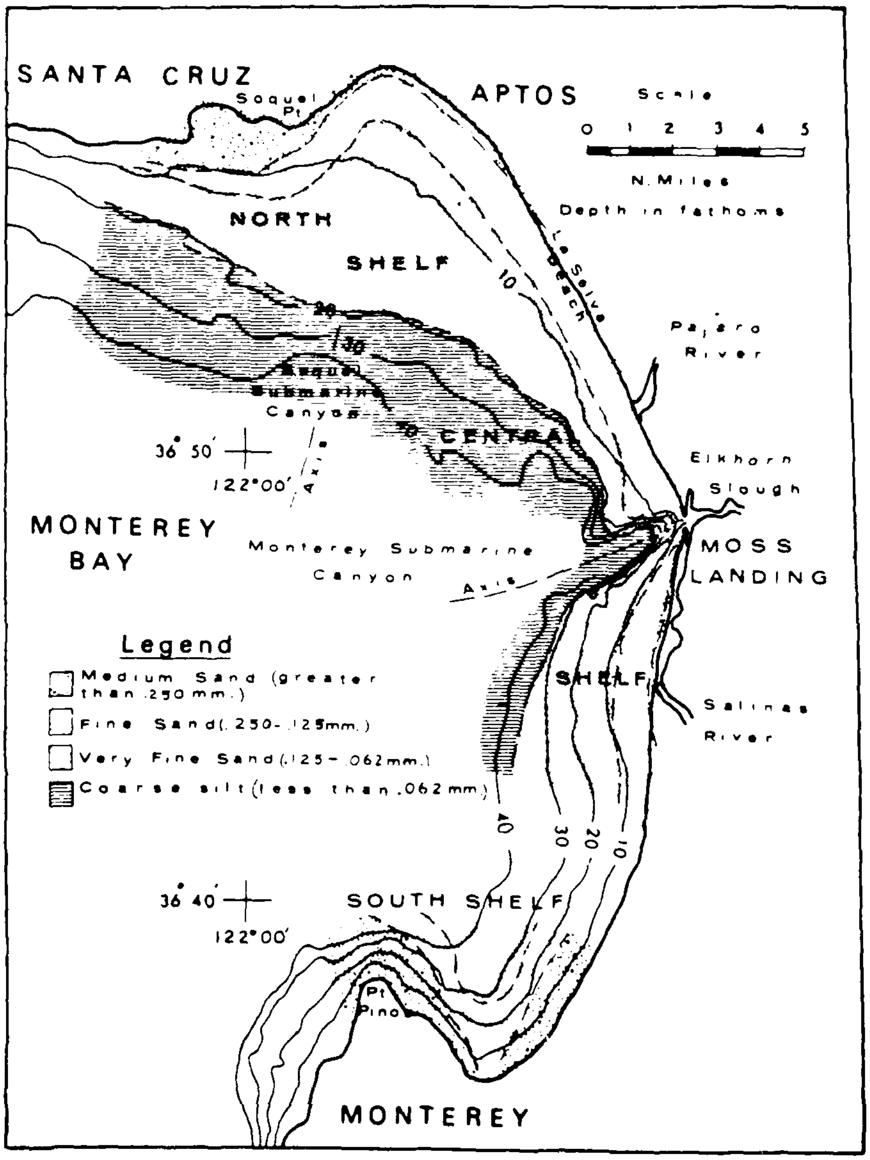


Figure 2-14. Distribution of median grain sizes in Monterey Bay [*from* Wolf, 1970].

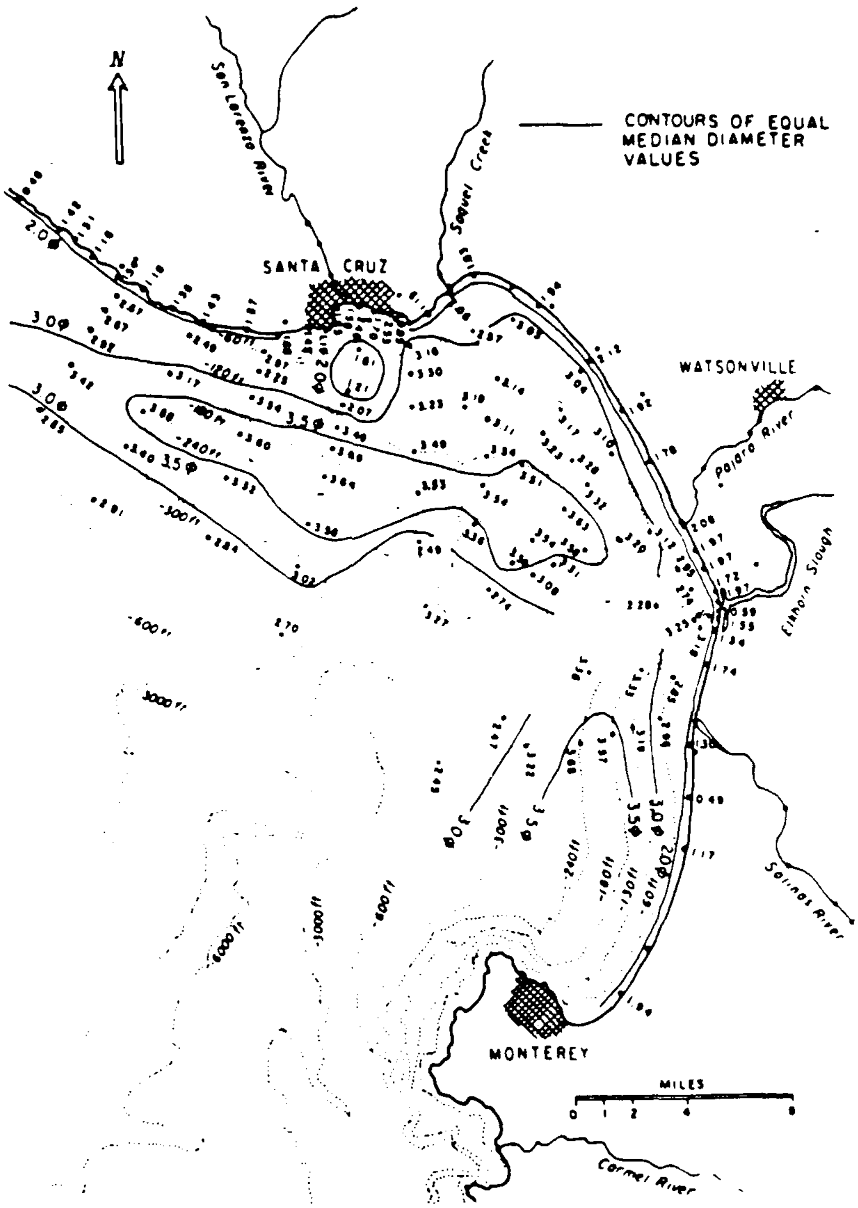


Figure 2-15. Distribution of median grain sizes in Monterey Bay [*from* Yancey, 1968, p. 27].

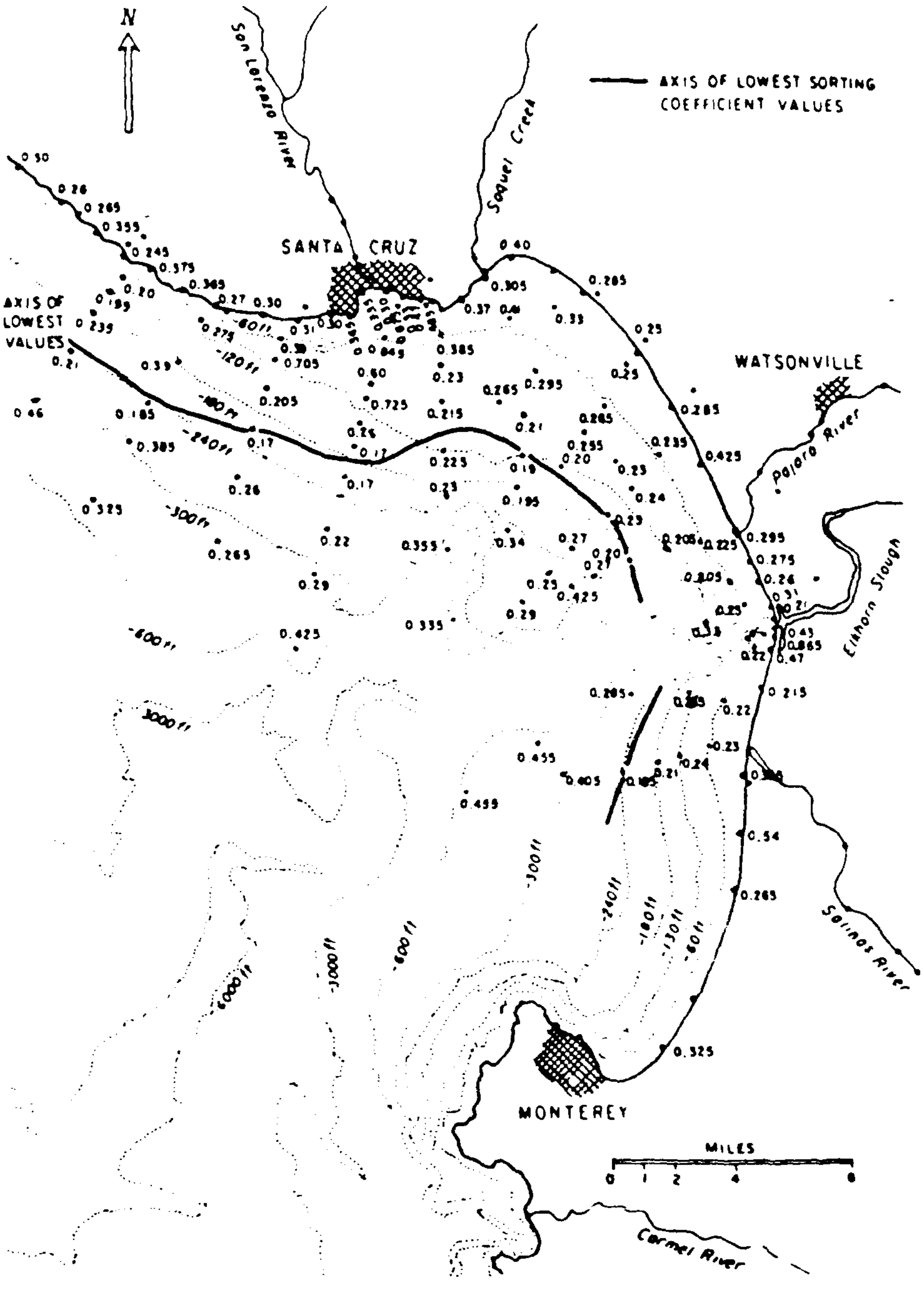


Figure 2-18. Phi sorting coefficient of the sand fraction of beach and marine samples [*from* Yancey, 1968, p. 29].

Peninsula. His distribution of mean grain sizes, which is shown in figures 2-17 and 2-18, parallels the others, but his sampling pattern delineated anomalies within the general pattern. Grain-size anomalies shown in figure 2-18 include the mushroom-shaped patch of medium-to-coarse sand that extends offshore from the beach at Sand City, the band of medium-to-coarse sand that extends northward from the mushroom patch in a depth of just under 20 m, and the shore-parallel band of medium-to-coarse sand in a depth of about 20 m off Fort Ord

Beach Sands

2.28. Monterey Bay beach sands are discussed in several papers. Galliher (1932) collected 34 beach samples from locations between Point Piños and Twin Lakes Beach; Sayles (1966) collected 41 samples between Point Santa Cruz and the Monterey Peninsula except on the beach at Fort Ord; Yancey (1968) collected 26 samples between Sand City and Point Santa Cruz and several more to the north; Dorman (1968) collected beach samples at 47 stations in his study area; and Combellick and Osborne (1977; also, Combellick, 1976) collected 36 samples, one-km apart, between Monterey Harbor and the beach 4 km north of the mouth of the Pajaro River. Dorman, Sayles, and Yancey collected samples at mid-tide level. Combellick collected them from a constant elevation (which was not specified) on the beach face, and Galliher did not specify where his samples were collected on the beach face. Together, the data give a good indication of the grain-size distribution along the bay's beaches. Figure 2-19 shows the grain-size distribution for most of the bay, Figure 2-20 is an example of the grain-size distribution for the beaches north of Monterey, and figure 2-21 shows in more detail the distribution for the central and south bay. Data from the Monterey Peninsula have not been plotted; that area comprises coarse-sand pocket beaches, and grain size increases from Monterey to Point Piños (Galliher, 1932, p. 55). Along the eastern shore of the bay, the sand was coarsest in the center of Fort Ord and decreased in size to both the south and north. To the south, grain size dropped from the largest value (about 0.9 mm in the center of Fort Ord) to the smallest (about 0.2 mm at Monterey Harbor) in about 11 km, and from 0.8 mm to 0.2 mm in about 5 km (fig. 2-21). To the north, grain-size changed gradually, reaching a mean diameter of just under 0.25 mm a couple of kilometers south of the Pajaro River mouth, a distance of about 17 km. Between there and Soquel Creek, median grain size fluctuated around 0.25 mm (the boundary between the fine and medium classes). Along the northern shore, median grain sizes fell in the middle to top of the medium-sized sand class, except for a sample on the west side of Soquel Point, which was coarse sand.

2.29. Combellick and Osborne (fig. 2-21) showed that seasonal variability in grain size depended on location. The largest differences between early and late spring occurred near the mouths of the Salinas and Pajaro Rivers. Around the Pajaro River, the late spring samples were coarser grained than the early spring ones; around the Salinas River, all but one of the late spring samples were finer grained than the early spring ones.

HEAVY-MINERAL PROVINCES

2.30. Combellick and Osborne (1977), Hutton (1959), Sayles (1966), Yancey (1968), and Yancey and Wilde (1971) all analyzed the heavy-mineral suites within Monterey Bay. Yancey (1968) separated his samples into size fractions and determined the heavy-mineral distributions in all the fractions. He found that heavy-mineral percentages were not a function of selective sorting, except for, possibly, apatite. Zircon, which often shows a tendency to concentrate in some size fractions, did not seem to be controlled by selective sorting in the bay. Also, density sorting was not important, but shape sorting was important in the finer sediments with respect to

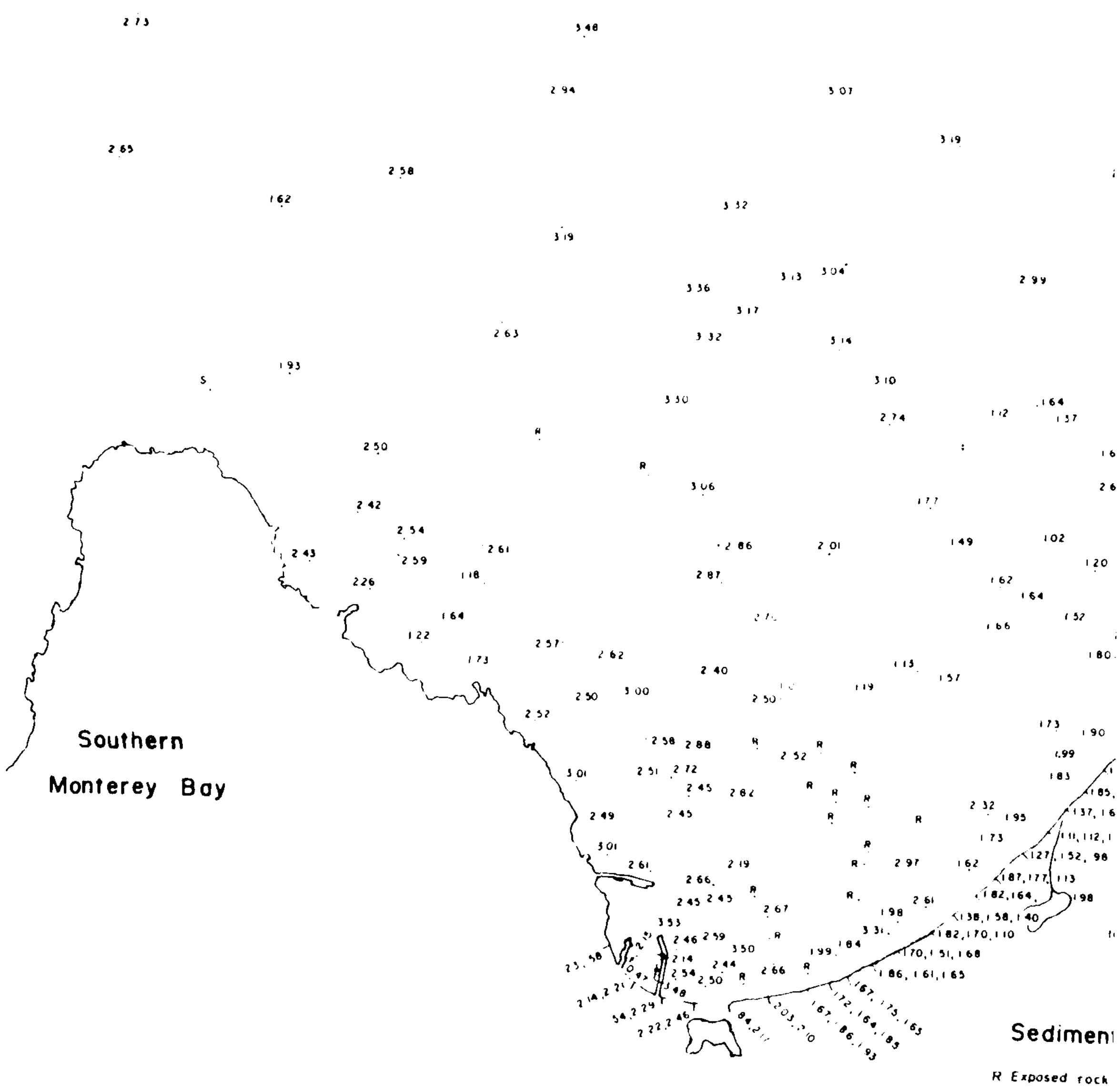
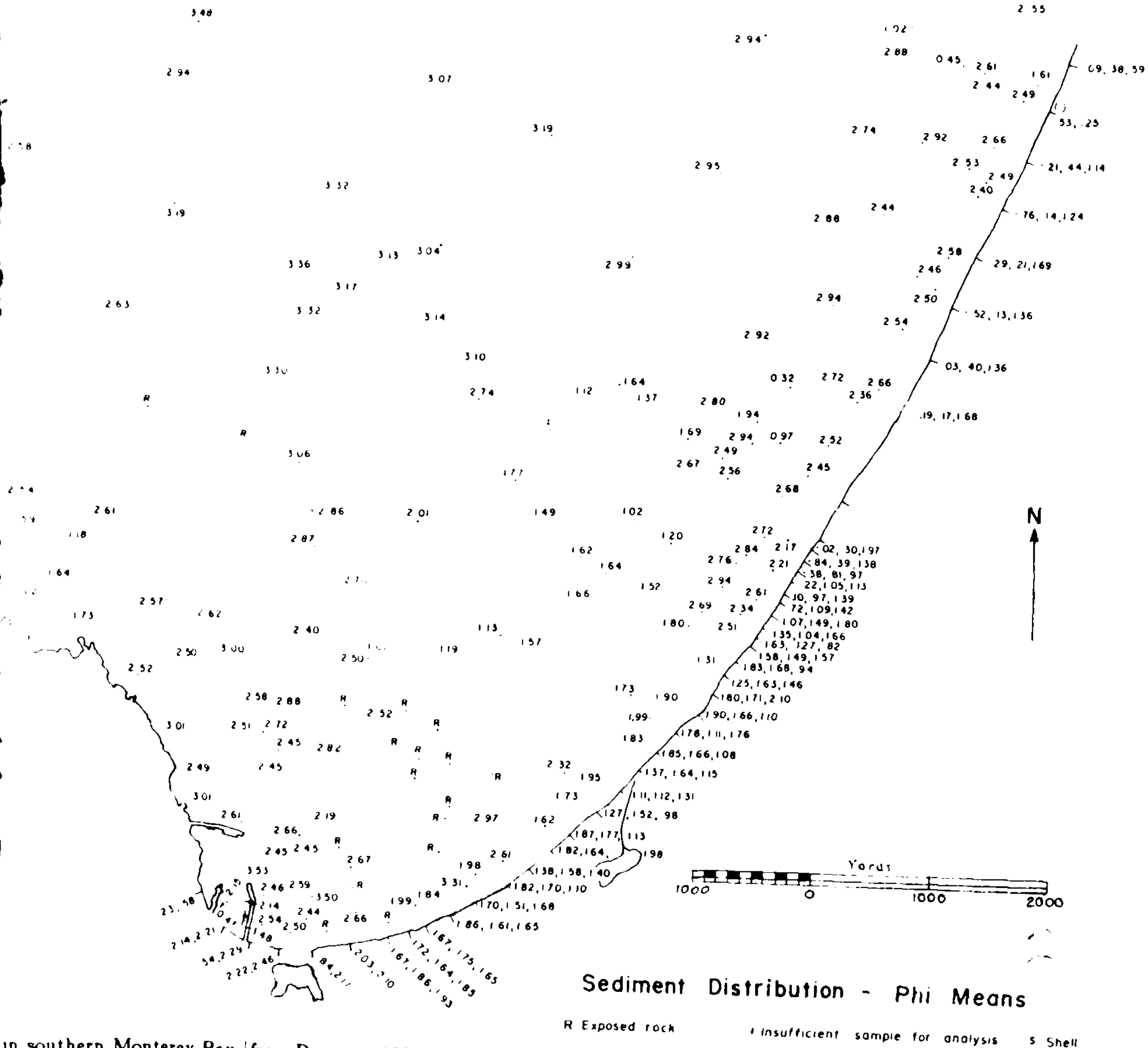


Figure 2-17. Distribution of median grain sizes in southern Monterey Bay [*from* Dorman, 1968, p. 34].



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in southern Monterey Bay [from Dorman, 1968,

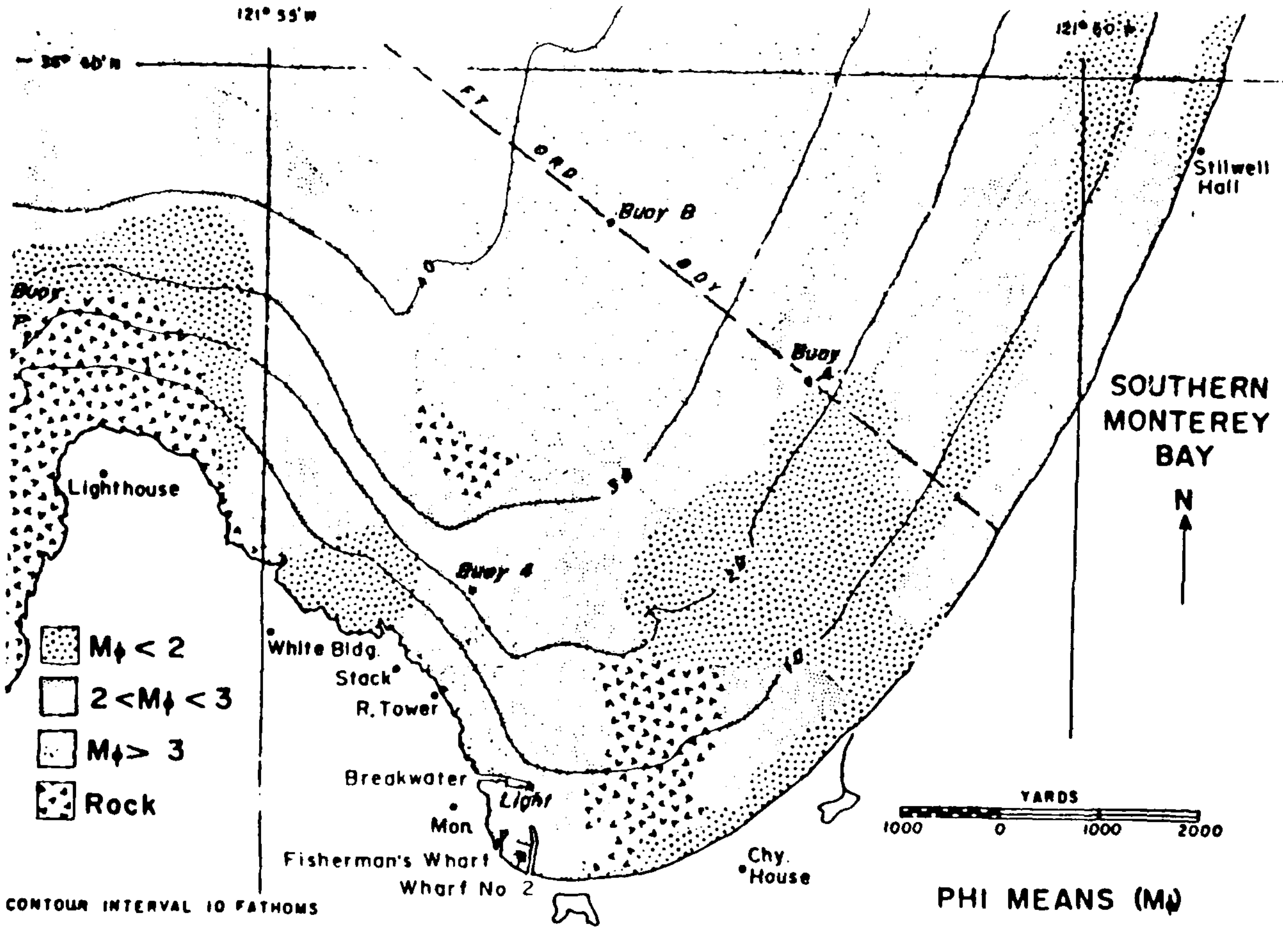
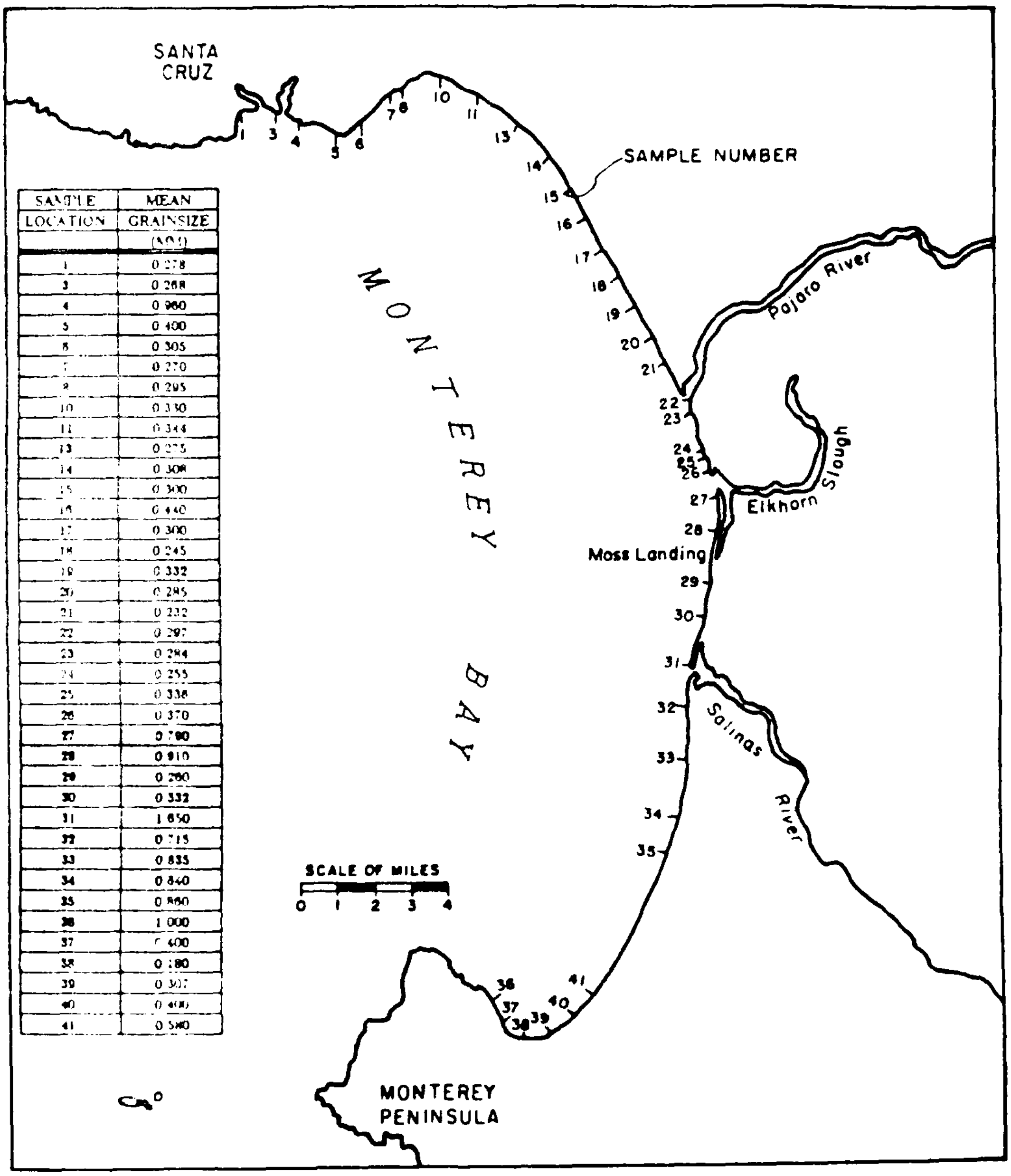


Figure 2-18. Interpretation of the grain-size distribution shown in the previous figure [from Dorman, 1968, p. 35].



SAMPLE LOCATION	MEAN GRAINSIZE (MM)
1	0.278
3	0.268
4	0.960
5	0.400
6	0.305
7	0.270
8	0.295
10	0.330
11	0.344
13	0.275
14	0.308
15	0.300
16	0.440
17	0.300
18	0.245
19	0.332
20	0.285
21	0.232
22	0.297
23	0.284
24	0.255
25	0.338
26	0.370
27	0.780
28	0.910
29	0.260
30	0.332
31	1.650
32	0.715
33	0.835
34	0.840
35	0.860
36	1.000
37	0.400
38	0.180
39	0.307
40	0.400
41	0.580

Figure 2-19 Distribution of median grain sizes (in mm) along Monterey Bay's beaches [*adapted from* Sayles, 1966, p. 3 and Appendix I].

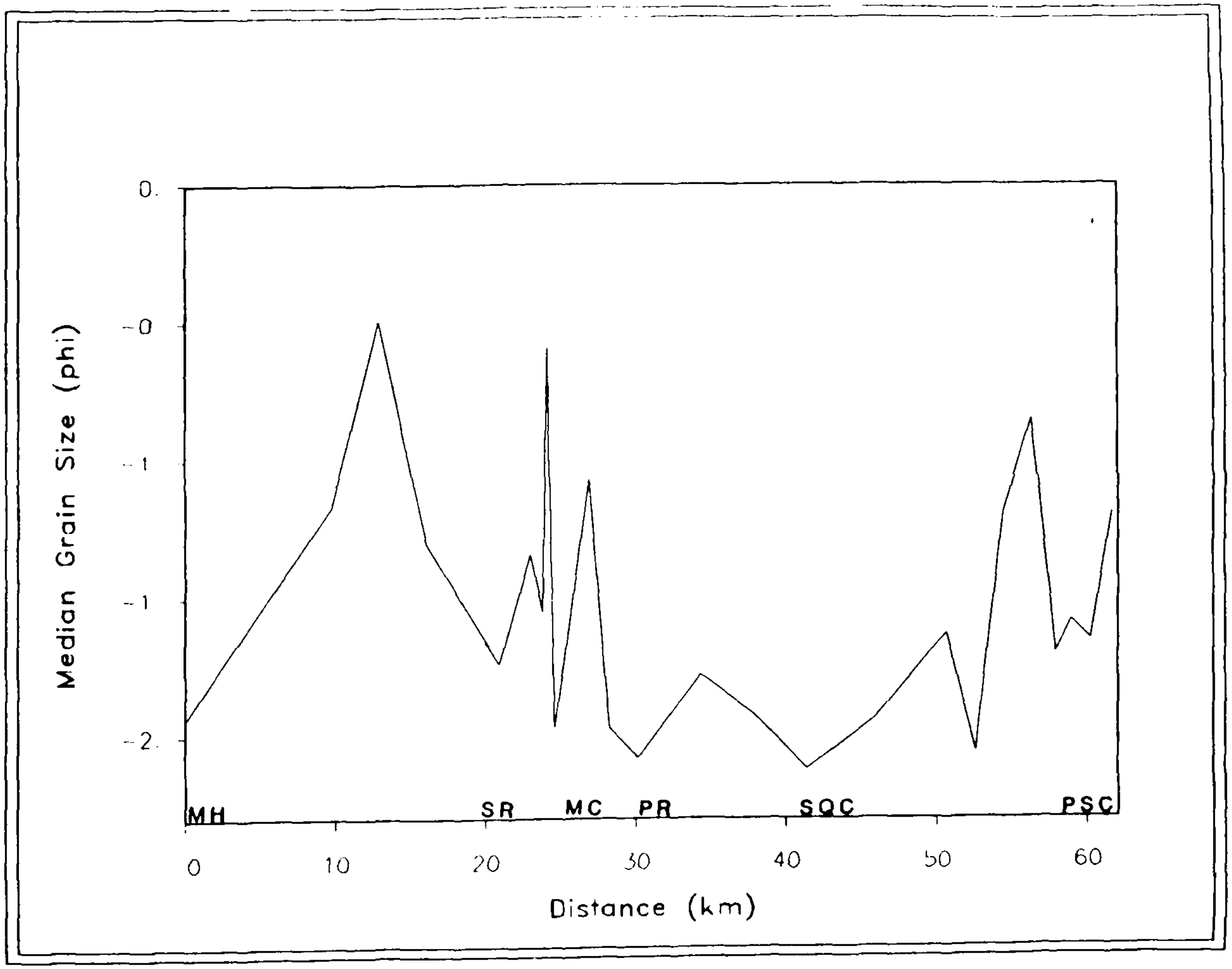


Figure 2-20. Distribution of median grain sizes as a function of the distance from Monterey Harbor (MH). Other symbols include: SR, Salinas River mouth; MC, Monterey Canyon; PR, Pajaro River mouth; SQC, Soquel Creek mouth; PSC, Point Santa Cruz [*adapted from* Yancey, 1968, Appendices A and C].

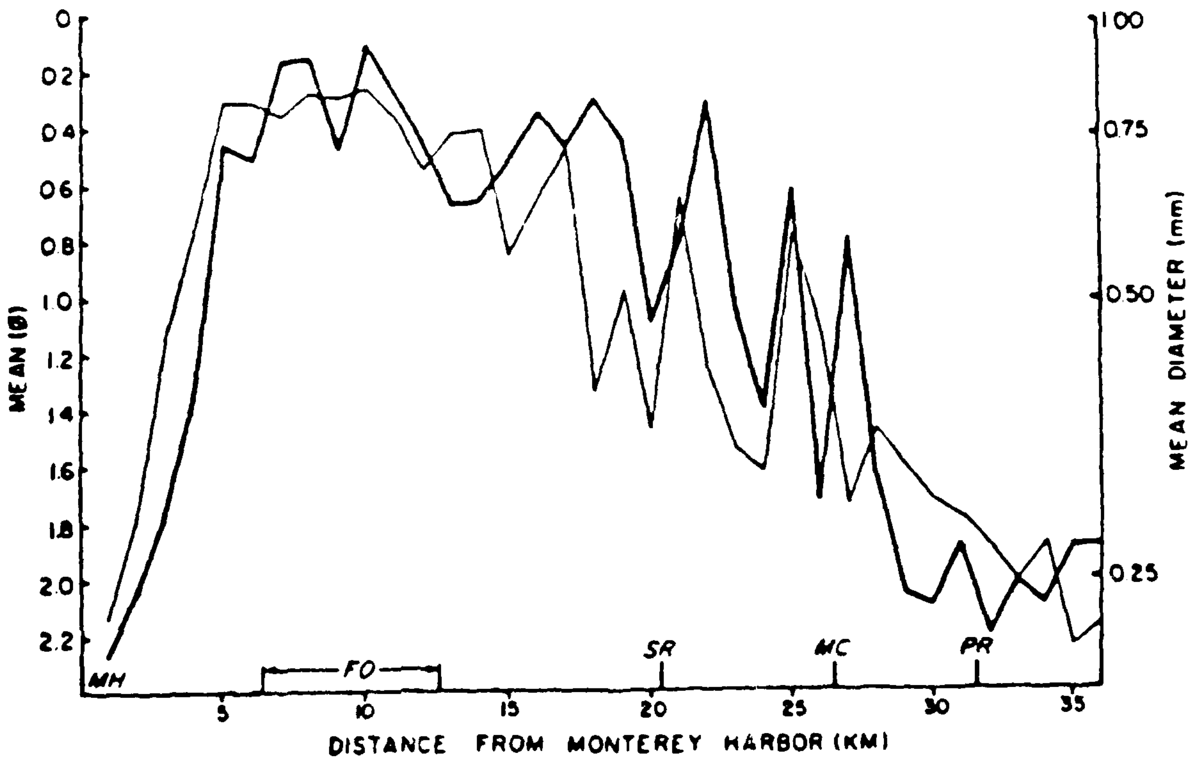


Figure 2-21 Distribution of mean grain sizes as a function of the distance from Monterey Harbor (MH) Other symbols include. FO, Fort Ord, SR, Salinas River mouth, MC, Monterey Canyon, and PR, Pajaro River mouth. The heavy line represents samples collected in February 1975 and the light line represent samples collected in June 1975 [from Combellick, 1976, p 22].

flakey grains.

2.31. Yancey (1968) divided Monterey Bay into four provinces based on the heavy minerals. These provinces, shown in figure 2-22, are:

1. The beaches and the nearshore off the mouth of the Salinas River. This province extended offshore to a depth of about 33 m and longshore from tne head of Monterey Submarine Canyon to Monterey. Offshore, it intergraded into province 2 over a distance of about 3 km. Distinctive heavy minerals were garnet (~ 10%) and brown hornblende; hypersthene was notably low in abundance. Bedload from the river had a similar mineralogy.
2. The offshore area west of province 1. Monterey Canyon bounded this province on the north and west. The province was without distinctive heavy minerals.
3. The northeastern part of the bay, extending from the shore to the edge of the shelf in the region off the mouth of the Pajaro River. Monterey Canyon was the southern boundary, and a line through the axis of Soquel Submarine Canyon to shore the northern boundary. The latter boundary was gradational with a 3-5 km mixing zone. Diagnostic heavy minerals came from Franciscan terrain, and lawsonite and jadeite were restricted to that province. Glaucophane concentrations were higher (~ 2%) than elsewhere in the bay.
4. A zone north of province 3 that extended to the north shore of the bay and from the east shore to the shelf break. The province was without distinctive heavy minerals.

Yancey also identified a fifth province that extended along the shore from Point Santa Cruz north to the limit of his samples. This province had a heavy-mineral suite high in augite (40%) and low in hornblende. The augite percentage was twice as high as in any of the other provinces. Table 2-5 lists the average values of heavy minerals found in the five provinces.

Heavy Mineral	Province				
	1	2	3	4	5
green hornblende	48.6	54.0	45.1	40.7	28.0
brown hornblende	10.7	5.0	4.7	4.0	3.7
oxyhornblende	1.7	1.9	3.6	4.4	2.0
augite	16.7	16.6	22.5	26.1	40.1
hypersthene	2.9	6.0	9.0	12.5	15.2
epidote	2.2	4.6	5.5	4.9	5.7
garnet	10.9	3.6	2.0	1.4	2.0
sphene	3.3	4.0	2.9	2.4	1.7
zircon	1.3	1.0	0.5	0.9	0.4
apatite	1.2	3.1	1.5	1.0	0.1
clinozoisite	0.1	0.3	0.4	0.5	0.4
detrital carbonate	0.2		0.1	0.4	0.1
glaucophane		0.3	1.6	0.6	0.2
lawsonite		0.5	0.1		
tourmaline		0.1		0.1	
staurolite	0.1				

Table 2-5. Average compositions of the heavy-mineral provinces [*after* Yancey, 1968, p. 70].

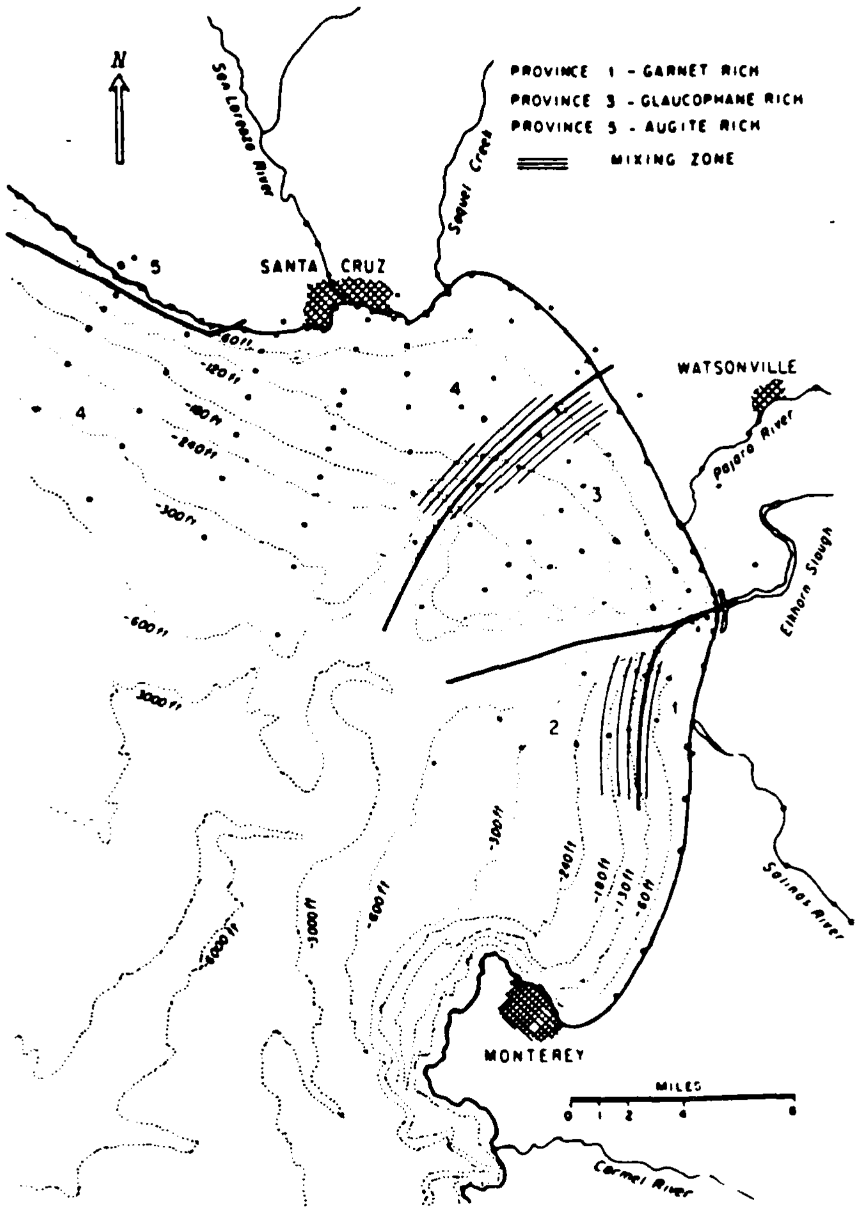


Figure 2-22. Heavy-mineral provinces in Monterey Bay [*from* Yancey, 1968, p. 68].

2.32. Though not identified by heavy-mineral techniques, Dorman (1968) found an area of different sediments along and just offshore of the Monterey Peninsula. This area would be adjacent to Provinces 1 and 2 above; it has a high shell-fragment content, subangular grains, and few heavy minerals.

2.33. Yancey found widespread uniformity in and similar proportions of the clay minerals in the samples from the offshore part of the bay. Those clays were identical to the clays from the Salinas and Pajaro Rivers and different from those from the San Lorenzo River, though the latter could have a low clay content in its suspended load.

Heavy Minerals of the Bay's Beaches

2.34. Hutton (1959) studied the heavy-mineral content of several beaches on the central California coast: magnetite and ilmenite made up much of the heavy-mineral fraction in his samples. He found high concentrations of blacksands just south of headlands and rivers and observed that the heavy-minerals were smaller in size than the quartz. Winnowing of a beach with high concentrations of heavy minerals caused the median grain diameter to decrease.

2.35. Sayles (1966) used variations in the percentage of four heavy minerals–hornblende, augite, hypersthene, and garnet–to separate the Monterey Bay beaches into four major provinces. Figure 2-23 shows the longshore variations in these heavy minerals; the provinces are:

1. Santa Cruz to Capitola. Hornblende, augite, and hypersthene were in the proportion 35:22:35, and garnet was low in concentration.
2. Capitola to Moss Landing. Hornblende, hypersthene, and augite were in the proportion 49:17:25, and garnet was low in concentration.
3. Moss Landing to Sand City. Hornblende, hypersthene, augite and garnet were in the proportion 60:4:10:26. Hornblende decreased from north to south in this province, and the boundary between province 4 and this one could have been in Fort Ord, where no samples were taken.
4. Sand City to Monterey. Hornblende made up more than 60% of the heavy-mineral assemblage, and the others occurred in minor amounts.

Sayles also determined that selective sorting was not responsible for the observed heavy-mineral distributions.

PROVENANCE

2.36. Yancey (1968) was able to assign a provenance to three of his five provinces. Briefly, he concluded that:

- The sediments in province 1 came from the Salinas River drainage area and were equivalent to the hornblende-garnet suite in the Pliocene deposits of the upper Salinas River Valley (Galehouse, 1967).
- The sediments in province 2 could not be assigned a provenance. Though the only source for southern Monterey Bay is the Salinas River, those sediments were different from those in province 2. The sediments in this province could be a mix of Monterey Peninsula and Salinas River sediments from a time of lower sea level.
- The sediments in province 3 came from the Pajaro River drainage area because it is the only river entering the bay that drains through Franciscan terrain.
- The sediments in province 4 could not be assigned a provenance. The heavy-mineral

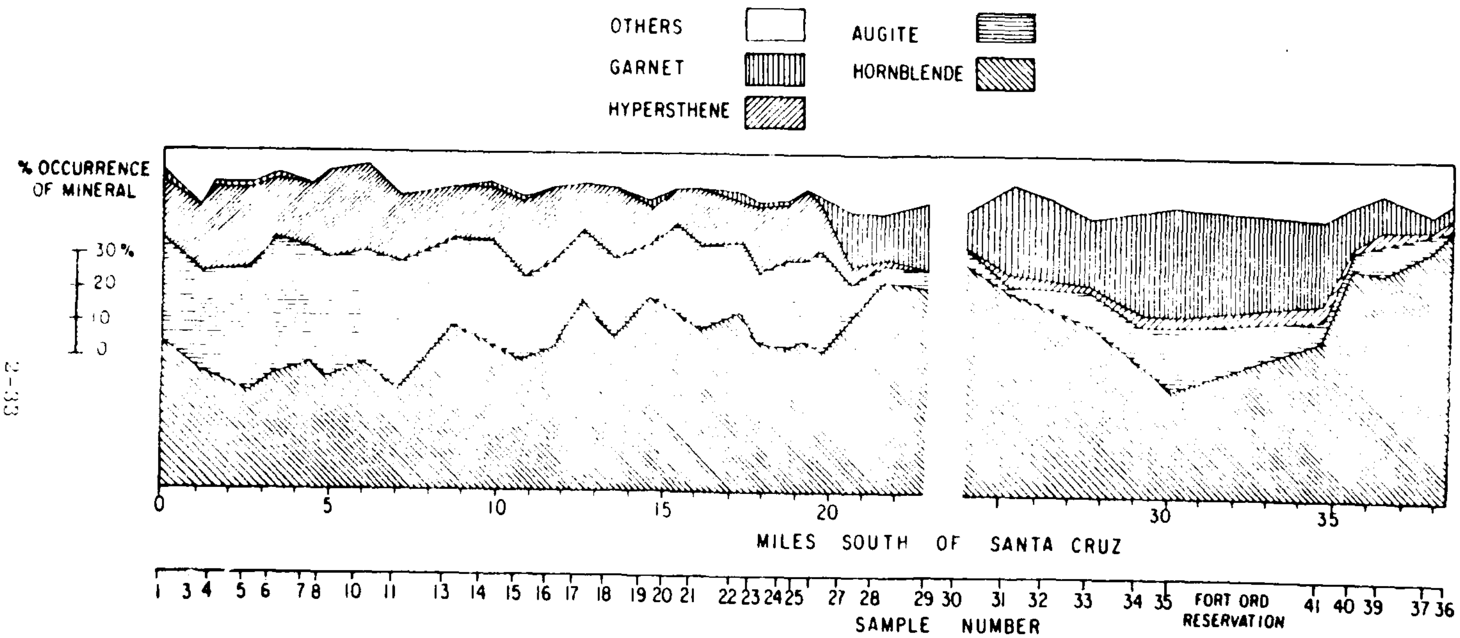


Figure 2-23. Heavy-mineral provinces on Monterey Bay beaches [*from* Sayles, 1966, p. 4].

distribution probably resulted from rapid mixing of various local sources. Even the San Lorenzo River with its high garnet content did not stand out.

-The sediments in province 5, which is outside the study area, mostly came from up-coast, probably from north of Santa Cruz county. The mineralogy of those sands differed from that of the cliffs and streams in the sample area, showing that those possible sources did not supply much sediment to the littoral zone.

2.37. Yancey also observed that the Pajaro River sediments are good tracers because they have unique heavy minerals; on the other hand, Salinas River sediments mix in too easily, and their signature is soon lost. He could only distinguish Pleistocene and Holocene on the basis of grain size and not mineralogy.

2.38. Both Sayles (1966) and Dorman (1968) concluded that the sediments in the south end of the bay came from the Monterey Peninsula. Sayles said that the high hornblende content of the sands in his fourth province came from the local granites. Galliher (1932) reported that the pocket beaches along the Peninsula were derived from the local granodiorite.

SUBMARINE-CANYON SEDIMENTS

2.39. Submarine canyons provide a conduit for sand to move from shallow to deep water, and a canyon that heads close to shore will funnel sand out of the littoral zone (Inman and others, 1976). Yancey (1968) found that sand from the axis of Monterey Canyon was mineralogically the same as sand on the adjacent shelves. Samples from the head of the canyon seemed to be a mixture of sand from provinces 1 and 3. Shepard (1963) found that the sediments in the canyon head were primarily fine sand and silt, but medium and coarse sand were also observed. In general, silt was more abundant on the canyon floor, while the ridges had coarser material. Three cores that he collected in the axis of the canyon contained alternating layers of medium sand and clay. No rocky material was collected except for a cobble and some gravel.

2.40. Wilde (1965) estimated that 1,000,000 m^3/yr of beach sand moved through Monterey Canyon and reached its fan; half of this sand came from north of the canyon and the other half from the Salinas River. Heavy-mineral distributions on Monterey Fan mimic those in Monterey Bay, with the northern side of the fan being a glaucophane province and the center and south sides being garnet provinces.

COASTAL MINING

2.41. In Monterey County, Quaternary stream deposits supply most of the gravel and much of the sand used in construction. Quaternary beach and dune deposits supply specialty sand along with sand and granules for construction (Hart, 1966, p. 84). Though the Salinas River has the most extensive sand and gravel deposits in Monterey county, little material is mined from it because it is considered unsuitable for most needs (Hart, 1966, p. 99).

2.42. Monterey Bay sand is commercially important because of its high silica content, hardness, grain roundness, amber color, and wide range of usable sizes (Combellick and Osborne, 1977). Medium and coarse sand are the most valuable, and mining operations are restricted to sections of the beach in southern Monterey Bay with high percentages of those fractions. More sand is mined in the winter when storms have enhanced the medium-and-coarse fractions on the beach. Hart (1966) reported that beach and dune sand has been mined since 1906 at various locations in southern Monterey Bay. To obtain the largest grain sizes possible, the mining companies dredge sand from the surf zone with dragline scrapers. Many of the plants also process dune sand, and at least one plant removes coarse sand from old beach deposits beneath the coastal dunes with a suction dredge (the water table is high enough to form a pond at the level of those deposits). The amount of sand removed by the mining companies is not accurately known because the State of California does not release those figures; however, one estimate is 230,000 m^3/yr (Combellick and Osborne, 1977).

2.43 The source of the medium-to-coarse sand is difficult to determine because the heavy minerals, which are often used to determine sand source, occur in low percentage and are found only in the finer sand fractions. Combellick and Osborne (1977) determined the provenance of the medium-to-coarse-grained sands by looking, instead, at grain-size distributions, lithologic compositions, and grain surface attributes. They sampled beaches north and south of Monterey Canyon, the Pajaro River, the Salinas River, the San Lorenzo River, the Flandrian and pre-Flandrian dunes that back the beach, a pocket beach along the Monterey Peninsula, the Aromas and Paso Robles Formations, and offshore sands. For the source of the southern medium-to-coarse-grained sands, they concluded that:

> landward migration of relict or modern offshore surface sand and wave erosion of pre-Flandrian and Flandrian coastal dunes are important sources, and there may be significant contributions from the Salinas River during flooding. Contributions by southward littoral transport across the head of Monterey Canyon, northward littoral transport from the Monterey Peninsula, offshore winds, and landward migration from offshore exposures of the Monterey, Paso Robles, and Aromas formations are negligible.

Porter and others (1979) also determined that the dunes were the major source of littoral sand in southern Monterey Bay and that the Salinas River contributed an insignificant amount of sand to the southern beaches because most of its sand moved north.

Physical Processes

2.44 Several physical processes are responsible for delivering energy to the littoral zone; energy that shapes beaches, erodes cliffs, transports and sorts sediments in both shore-parallel and shore-normal directions, and damages coastal structures. Most of the energy that is dissipated in the littoral zone comes from processes that originated at sea, though stream runoff and offshore winds can also be important (Inman, 1971). Figure 2-24 shows a general budget of energy and land runoff in the coastal zone. These processes differ in strength and period from a few seconds (waves) to tens of years (sea-level change). Though an intense storm may instantly cause significant erosion, the slow rise in sea level may be just as significant in terms of coastline retreat.

2.45 This section discusses the shorter time-scale physical processes that affect Monterey Bay. Waves are by far the most important source of energy for the coastal zone. Coastal currents are relatively unimportant in the littoral zone; however, they control the movement of silty and clay material in the outer part of the bay. Tidal currents are weak along the coast but possibly affect sediment movement within Monterey Canyon. The rise and fall of the tide, as well as other processes that alter sea level for short periods of time, are important processes in the littoral zone because they expose a range of beach elevations to wave attack. Winds, another energy source, affect littoral-zone sediments by blowing them both on- and offshore. Fluvial processes are discussed in detail in the Chapter on *Basin Sediment Resources*, and will only be touched upon here.

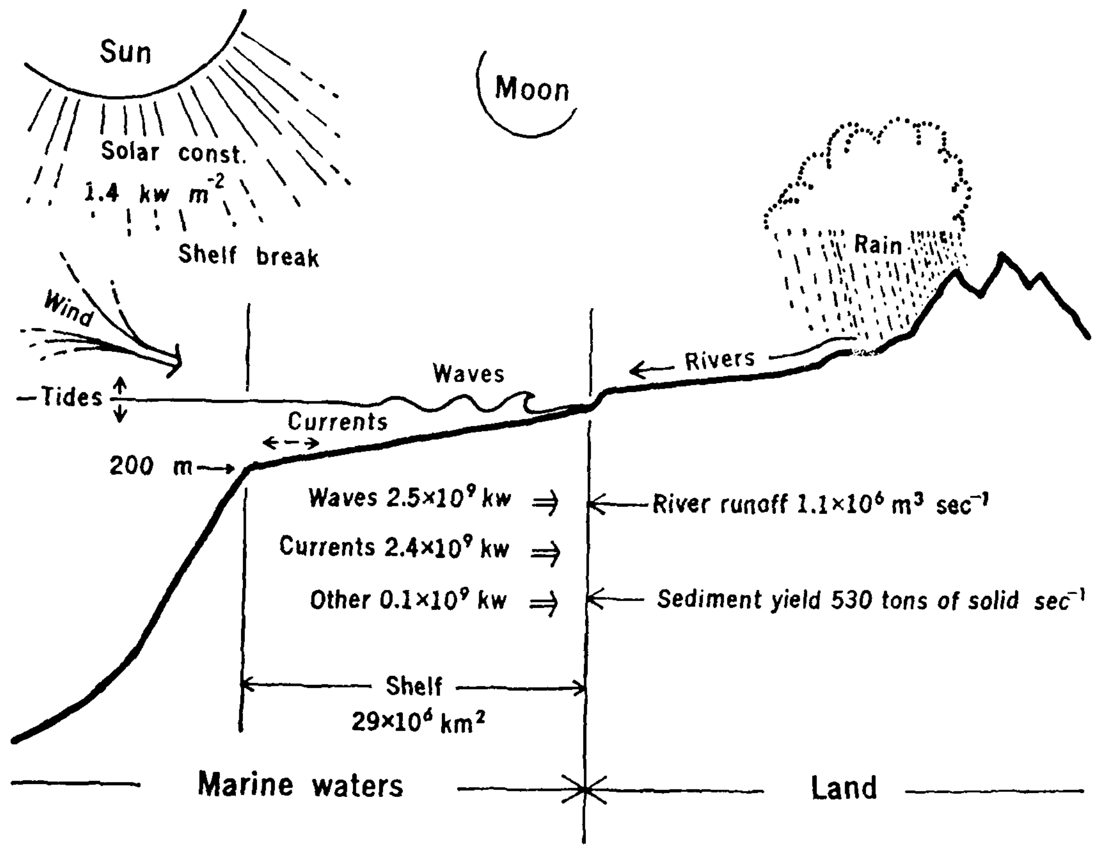


Figure 2-24. Budget of energy and land runoff in the coastal zone [*from* Inman, 1971].

WAVES

2.46 This section summarizes the basic shallow-water wave processes and how they affect Monterey Bay. Detailed wave data that apply to Monterey Bay are available from National Marine Consultants (1960), Meteorology International, Inc. (1977), and various reports of the Nearshore Research Group.

2.47 At least four processes can alter the height of a wave in shallow water–shoaling, refraction, interactions with other waves, and breaking. Shoaling is the process whereby waves shorten in length and ultimately increase in height because their motion impinges on the bottom. Refraction is the process whereby wave crests diverge or converge as they try to adjust to changes in the bottom topography. The part of a wave crest that travels over a submarine canyon will move faster than the parts over the adjacent shelf, and shoreward of the canyon, the wave height will be significantly smaller than on the flanks of the canyon. Shepard (1963) reported that waves shoreward of the head of Monterey Canyon could be 10 or 20 times smaller than waves on its flanks. Refraction into bays tends to reduce wave height, while refraction around headlands tends to increase it. In deep water waves only interact weakly with other waves; in shallow water, however, wave-wave interactions can produce strong interchanges of energy (Inman, 1971). For example, when incident waves interact with edge waves, which travel along the shore, each wave crest is modified such that it has alternating high and low areas, and the low areas mark the positions of rip currents. Wave breaking results in a decrease in wave height and the release of energy in the form of turbulence. After breaking, the wave continues to travel shoreward in the form of a bore; both the breaking process and the movement of the bore across the surf zone produce rapid suspension and mixing of the underlying sediments that alternates in the onshore and offshore directions (Inman and Brush, 1973). Furthermore, if the waves break at an angle to the shore, they generate a longshore movement of sand in the down-wave direction.

2.48 The ability of a wave to move sediment is directly proportional to its energy, which is directly proportional to the square of its wave height. Wave period determines the depth at which a wave starts shoaling, and, therefore, the degree to which it refracts before breaking. The strength of the longshore current is proportional to the breaker angle with the maximum being at 45°. Also, coastal damage is greatest when wave run-up is greatest, which occurs when the wave period is longest (Bixby, 1962, p. 23).

Wave Climate

2.49 Deep-water waves characteristically come from the northwest with heights between 0.6 and 6 m and periods of 4 to 20 s. Storms come from all possible directions with the largest ones coming from the west or southwest in the fall or winter months. Storms with deep-water wave heights in excess of 5 m occur 5 times a year on the average, and storms with wave heights in excess of 6.5 m occur once every 9 years. Beaches in parts of Monterey Bay were extensively eroded and homes damaged during the winters of 1977-78 and 1982-83. Damage exceeded $18,000,000 during the former winter and $100,000,000 the latter (Griggs and Johnson, 1983). The storms during those winters usually took more southerly storm tracks than normal (Dormurat, 1978, Seymour and others, 1985), and were coupled with unusually high tides and an intense El Niño event. The storms of the 1982-83 winter had the longest wave periods and heights of all storms hindcast from 1900 (Seymour and others, 1985).

Littoral Drift

2.50. Because Monterey Bay is an embayment, each incoming wave train is going to affect parts of the bay differently. For example, waves from the northwest, which is the dominant wave direction along the California coast, have to refract strongly to reach the northeast corner of the bay. This results in a divergence of the wave crests and a decrease in the energy per unit crest length Griggs and Johnson, 1983). Waves from the southwest, however, refract very little before reaching the northeast corner of the bay. This means that the energy per unit crest length decreases very little for those waves. The U. S. Army Corps of Engineers (1958) described wave refraction patterns for the coast from Año Nuevo to Point Piños. They found the following:

1. For Año Nuevo to Natural Bridges State Beach (just west of Point Santa Cruz) all wave directions produce divergence with waves from the southwest quadrant diverging the least and waves from the northwest quadrant the most.
2. For Natural Bridges to New Brighton State Beach waves from the west and northwest are greatly refracted and the latter reach shore from the southwest with large divergence and height reduction. Southwest waves refract much less.
3. For New Brighton to Moss Landing northwest waves respond as in (2) while west and southwest waves converge and diverge depending on period and direction. Refraction coefficients increase to the south except at Moss Landing, where the canyon head causes divergence.
4. For Moss Landing to Monterey Harbor the wave patterns were like in (3). Refraction coefficients increase to the mouth of the Salinas and then decrease to the harbor.
5. For Monterey to Point Pinos refraction causes northwest waves to diverge; west and southwest waves diverge greatly, which greatly reduces their energy.

2.51. Other observations agree in general with the patterns just described. Bascom (1954) explained the natural tendency of the Salinas River to flow northward and enter the bay north of Elkhorn Slough by explaining that a stream will break through its berm at the point where the refraction coefficient is lowest (and therefore, the wave energy is lowest). Because the refraction coefficient decreases toward the canyon, the Salinas River would naturally tend to flow into the ocean at the canyon. Johnson (1953) however suggests that littoral transport is close to zero within Fort Ord. He argues that the higher the refraction coefficient, the more parallel the wave crests must be to the shore; therefore, littoral transport must be lowest in that area.

2.52. The U. S. Army Corps of Engineers (1958) also described the longshore transport patterns to be expected for different wave directions. With respect to the five categories discussed above, these patterns are as follows:

1. South for all wave directions except southwest and south, which produce northward transport north of Davenport only.
2. Downcoast except that waves from the south produce upcoast transport at Twin Lakes Beach. Most waves break at a large angle with the shore, implying a large magnitude of downcoast transport.
3. Southward transport for northwest and west wave directions, and northward transport for southwest and south ones. Westsouthwest wave directions produce northward transport north of Manresa State Beach; southwest and south directions do the same north of Aptos Creek.

4. South for waves from north of west, except northeast of Monterey Harbor where the angle is zero or transport is to the north. West and south-of-west directions produce transport to the north.
5. All waves produce transport toward Monterey Harbor.

2.53. Dorman (1968) recognized a divergence zone around the southern boundary of Fort Ord that corresponds with the area where the refraction diagrams show the longshore transport direction reversing in the southern part of the bay (4 above). The lack of change on the beaches adjacent to the Moss Landing jetties is consistent with a divergent drift pattern at the head of Monterey Canyon (Wong, 1970). The growth of Seabright Beach and the retreat of Capitola Beach after construction of Santa Cruz Harbor support eastward littoral drift in north bay (Griggs and Johnson, 1983).

2.54. The rate of littoral drift is not well known in Monterey Bay except along its northern boundary where the Santa Cruz Harbor acts as a sediment trap. Griggs and Johnson (1976) and Hicks (1985) are among those who have estimated that about 230,000 m^3/yr reach the harbor from the west. Wilde (1965) estimated that 500,000 m^3/yr reached Monterey Canyon from the north and an equal amount reached it from the south. This means that 270,000 m^3/yr are added to the northern bay between Santa Cruz Harbor and the canyon. Because the major supply of sand from the south is the Salinas River, Wilde's estimates, which were based on data from the Monterey Fan, may be too high now that the Salinas River no longer empties into the canyon head, and now that there are three dams on the Salinas River.

CURRENTS

2.55. Currents supply less energy to the littoral zone than do waves. However, slow-moving currents can transport sediment suspended by waves and are important in moving fine-grained sediments in deeper water. Currents that operate in Monterey Bay include littoral-zone currents, coastal currents and gyres associated with them, shelf seiches, and a hydraulic current on the beach side of the north jetty at Moss Landing. Seiches are not well understood, but currents of this type may be important in generating down-canyon flows during storms (Inman and others, 1976; Robinson, 1969).

2.56. Outside Monterey Bay, the California Current flows to the south throughout the year; it only flows nearshore in October and early November (Dorman, 1968). The Davidson Current flows to the north inside the California Current from November to February. These currents are slow along the open coast and slower within the bay (Griggs, 1974).

TIDES

2.57. Monterey Bay tides are diurnal in nature. The diurnal range is 1.6 m, the mean range is 1.1 m, highest high water is 2.4 m, and lowest low water is -0.8 m. Storm tides vary with conditions; Dean and others (1984) estimated that the maximum set-up during the 1982-83 storms was about 0.5 m.

WIND

2.58. Wind records for Monterey Bay are sparse; the prevailing winds are from the west or southwest (U. S. Army Corps of Engineers ,1958). Galliher (1932) decided that dune orientation in southern Monterey Bay indicated a northwest direction for the prevailing winds. He showed how a northwest wind pattern would be consistent with having a transport minimum in the Fort Ord region (fig. 2-25). Bixby (1962) found that violent northwest-to-northeast winds occasionally damaged boats and structures in Monterey Harbor. Those local windstorms, which he associated with a weather type similar to the one that causes Santa Ana winds in southern California, only blow over the bay; therefore, the waves are limited to a fetch of less than 50 km.

RIVERS

2.59. Rivers are often thought to be suppliers of sand to the littoral zone, but often they can also extensively erode the beaches through which they flow. Dingler and others (1985) showed that the Salinas River eroded the beach north of its mouth during the summer of 1983. Hicks (1985) showed that the large delta formed at the mouth of the San Lorenzo during 1982 and 1983 altered the littoral transport in the vicinity of the Santa Cruz Harbor.

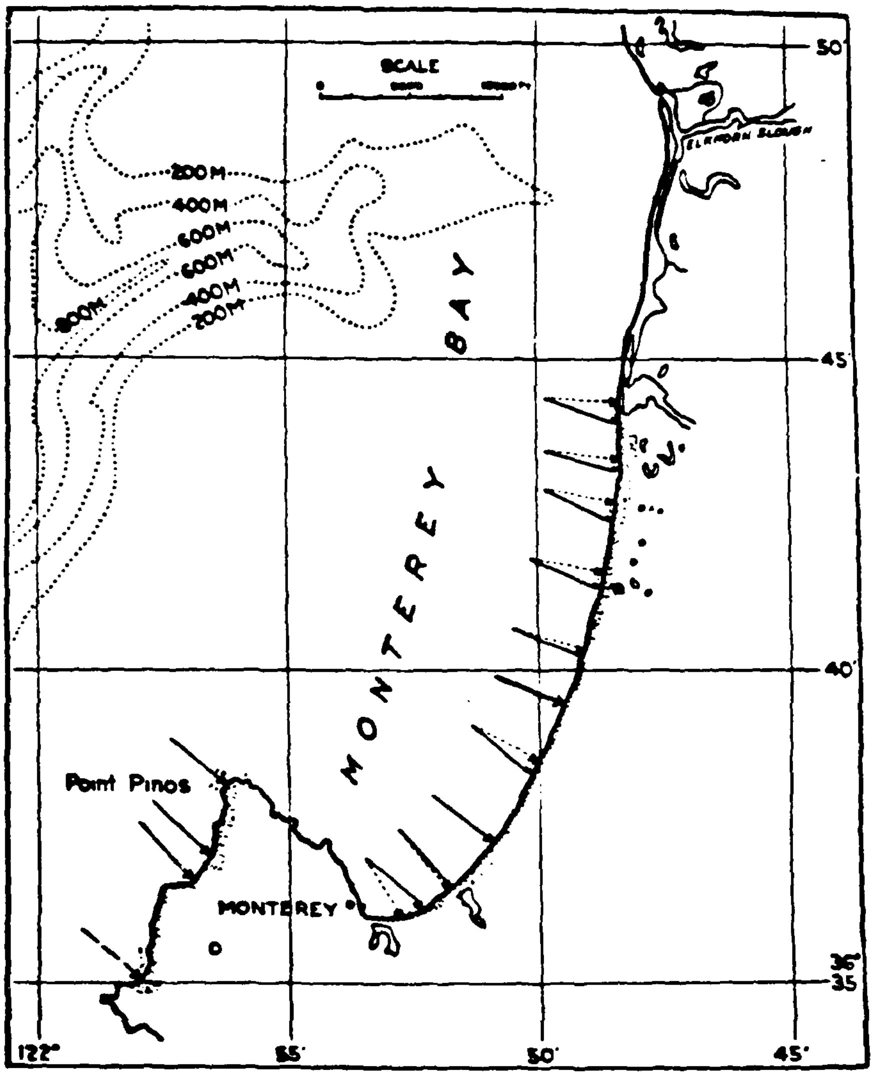


Figure 2-25. Vector analysis of the wind force that impinges on the shore of southern Monterey Bay. The alignment of the dunes are used as a rough indication of the direction of the wind force. The wind indirctly controls the movement of sand along the beach [*from* Galliher, 1932].

3. BASIN SEDIMENT RESOURCES

3.1. Streams and rivers are the principle source of littoral sediment in most coastal areas. To evaluate the importance of streams and rivers in supplying sand to the Monterey Bay beaches, this chapter will describe each of the major drainage basins, describe distinctive characteristics for those sediments transported from each of the major drainage basins to the littoral system, and present approximate sediment yields for each river that inputs sediment.

Basin Characteristics

EXTENT

3.2. The drainage system currently contributing sediment to the Monterey Bay littoral zone is made up of three drainage basins: the San Lorenzo, the Pajaro, and the Salinas (fig. 3-1). These three basins cover a total area of about 15,500 square km.

3.3. The Salinas basin, the largest of the three drainage basins that supply sediment to Monterey Bay, trends to the southeast and covers about 11,400 square km (fig. 3-1). The Gabilan and Diablo Ranges form the eastern boundary and the Santa Lucia Range forms the western boundary. Topographically, the area consists of mountain ridges with peaks as high as 1500 m, and a broad intermountain valley, the Salinas Valley. The latter, changing topographically little throughout its length, has a low gradient and is covered in many areas by alluvium. The main channel of the Salinas River, the only river in the Salinas basin that inputs sediment into the bay, is about 270 km long and has a general northwesterly course; however, only the lower 150 km meanders through the valley floor.

3.4. The Pajaro basin abuts the Salinas basin on the north-west and includes the Santa Clara, San Benito, and Pajaro Valley sub-basins (fig. 3-1). The Santa Clara and San Benito sub-basins, both of which trend southeast and cover a total area of about 3,370 square km, are bounded on the southeast by the Diablo Range, on the northeast by the Santa Cruz Mountains, and converge on the west side at the Pajaro Gap at Chittendon. The Santa Clara and San Benito sub-basins drain westward toward Monterey Bay through the 180-meter-deep Pajaro Gap, which cuts across the northern extension of the Gabilan Range. The Pajaro Valley sub-basin, a triangular shaped basin formed by the western slope of the Santa Cruz Mountains and the northern extension of the Gabilan Range, covers about 112 square miles. East of the Pajaro Gap, the Pajaro basin consists of mountain ridges with peaks over 1,200 m high, while west of the gap it is a gently seaward-sloping alluvial plain. The main channel of the Pajaro River, the only river in the Pajaro basin that inputs sediment into the bay, is about 45 km long and has a general westerly course; however, only the lower 20 km meanders through the Pajaro Valley floor.

3.5. The San Lorenzo basin, abutting the Pajaro basin on the northwest, includes the San Lorenzo, Aptos, and Soquel sub-basins (fig. 3-1). All three sub-basins, which generally trend north-south and cover a total area of about 5180 square km, are bounded on the north and northwest by the Santa Cruz Mountains. Topographically, the area has predominantly rugged mountains over 300 m in elevation; and, unlike both the Pajaro and Salinas basins, the San Lorenzo does not contain a broad alluvial plain. Debris flows, block slides, and debris slides commonly occur in this basin (Brown, 1973; Griggs, 1982). The San Lorenzo River, Soquel Creek, and Aptos Creek all input sediment into the bay. The San Lorenzo River, the major

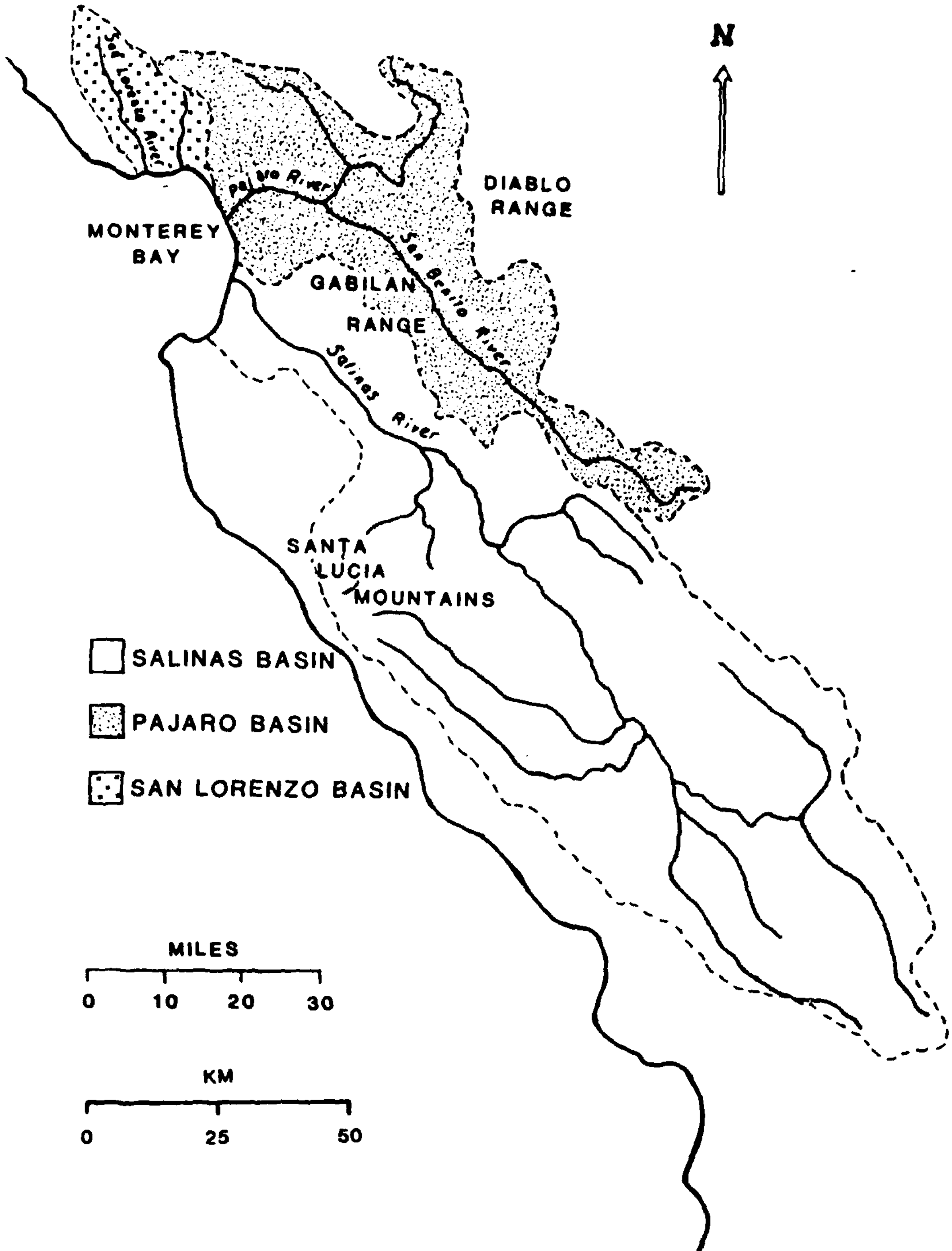


Figure 3-1. Drainage basins and mountain ranges adjacent to Monterey Bay [*adapted from* Yancey, 1968]

river in the basin, flows southward for about 32 km from its head to the bay; only the last 4 km flows through a small flood-plain district.

TOPOGRAPHIC VARIATION

3.6. Figure 3-2 shows river bed elevation versus distance from the coast for the three major rivers that empty into Monterey Bay (Salinas, Pajaro, and San Lorenzo). The San Lorenzo River has an extremely steep gra· ·nt (17 m/km) in comparison to both the Pajaro (5 m/km) and the Salinas (1 m/km). This reflects the steep, rugged terrain in the San Lorenzo basin versus the broad, alluvial plains on the lower reaches of the Pajaro and Salinas basins. River channel gradient is an important characteristic since it is proportional to sediment discharge per unit stream width (Komar, 1976).

SURFACE-WATER FLOW

3.7. Stream discharge records, although not always directly proportional to sediment discharge, can represent the potential of a drainage system to transport sediment into the littoral zone. Within the Monterey Bay drainage system, over 90% of the stream discharge occurs during the months of December through May; therefore, most sediment transport to the beach takes place during large storm events within this interval of time (U.S. Army Corps, 1983). In fact, both the Pajaro and Salinas Rivers are fronted by beach bars during most of the year and only input sediment during large storms when high runoff breaches these bars. However, surface-water flow in all three basins varies greatly from year to year and one must examine the long-term record to discover significant trends.

3.8. The 40-year record (1941-1980) of surface water flow for the three major rivers that empty into the bay, which was compiled from U.S.G.S. stream-gage data, illustrates two major trends (fig. 3-3). First, similar yearly variations suggest that climatic conditions are similar in all three basins; however, the San Lorenzo basin receives more rainfall than either the Pajaro or Salinas. Second, although the San Lorenzo basin is roughly one-tenth the size of the Pajaro basin, the two basins have roughly equal average surface-water flow rates. This results from the extreme differences in topography. Stream discharge per unit area is much higher in more mountainous areas. The San Lorenzo basin has steep, rugged terrain, mostly over 300 m in elevation, and the Pajaro basin has rather low, flat terrain. In addition, the San Lorenzo basin contains a bedrock-floored valley, which channels most water into surface flow, whereas the Pajaro and Salinas basins channel appreciable amounts of water into subsurface water flow through their alluvial deposits (Yancey, 1968).

HISTORICAL CHANGES

3.9. Several historical events, both natural and man-induced, have caused changes within the three drainage basins. The most dramatic natural event occurred in 1908-1910 when the Salinas River changed its course. Before 1908, the river entered Monterey Bay about 1.6 km north of Moss Landing. Between 1908 and 1910 the river began to empty into the bay at its current location, about 7.2 km south of Moss Landing (Gordon, 1979). This change in river mouth location is extremely significant when considering the bay's sediment budget since the pre-1908 location was north of the Monterey submarine canyon, and, therefore, most river sediment, which is now deposited on the southern beaches, moved directly into the north end of the canyon head. In the early part of this century (1926-1934) the river still showed a strong tendency to flow northward into its pre-1908 position; however, man-made earthen dikes and levees currently

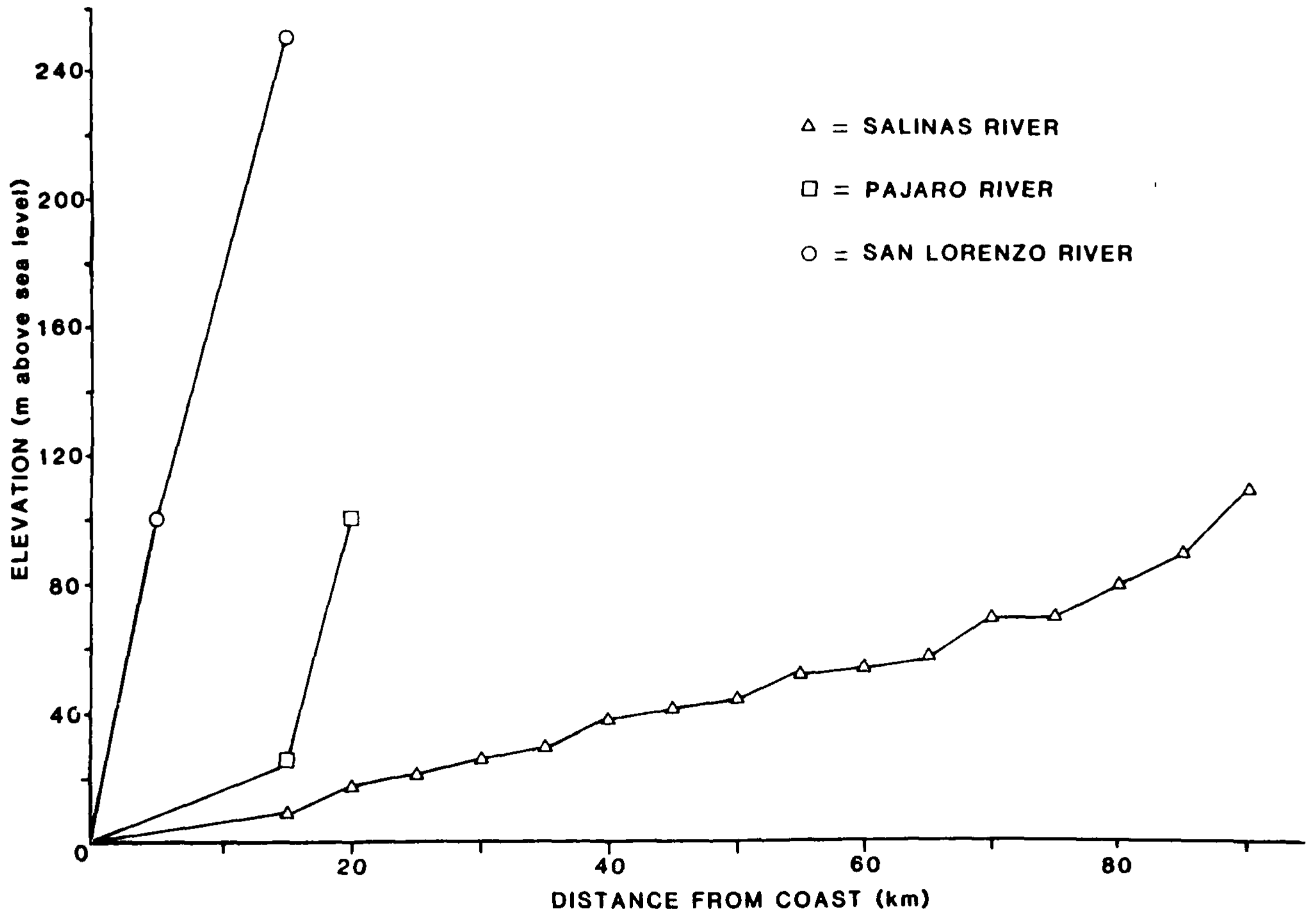


Figure 3-2. Stream gradients for the Salinas, Pajaro, and San Lorenzo Rivers

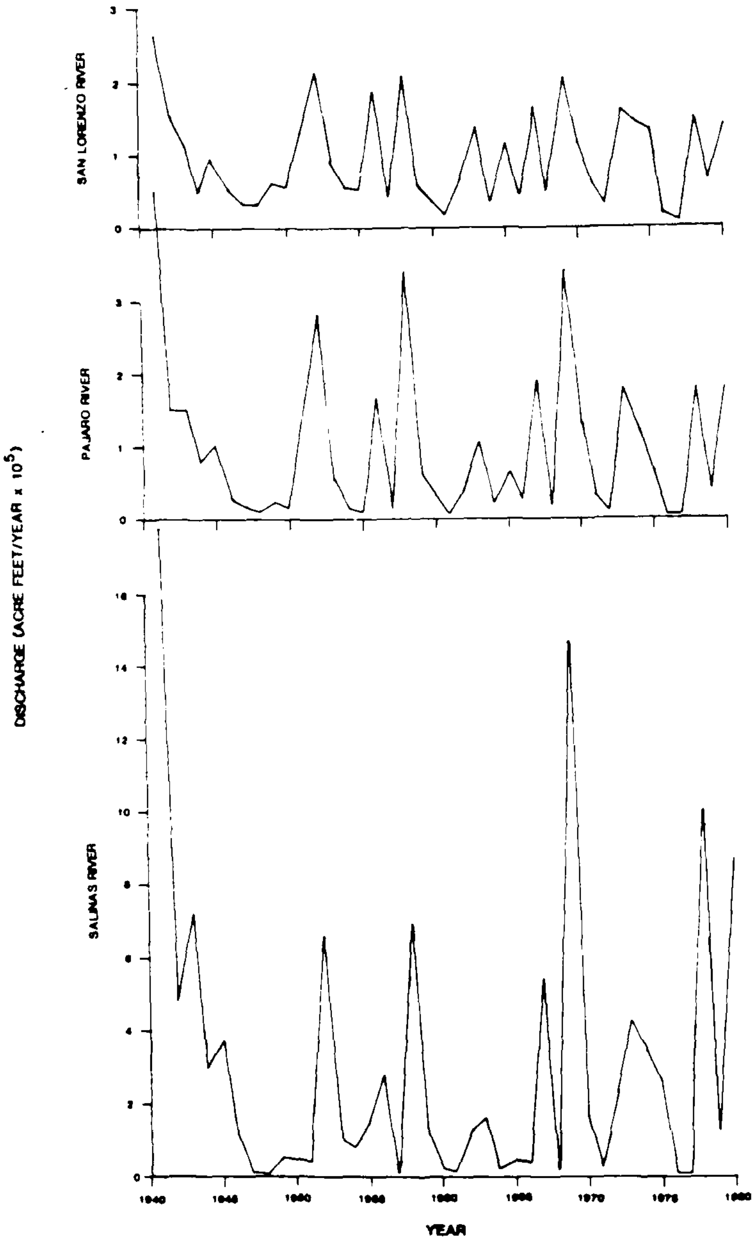


Figure 3-3. 40-year record (1941-1980) of surface-water flow for the Salinas, Pajaro, and San Lorenzo Rivers

prevent any northward flow (Gordon, 1979). The current river mouth is separated from the bay by a wide beach bar, which is opened annually in October or November by the Monterey County Flood Control District as a flood-control measure.

3.10. Four man-induced activities have significantly changed the character of the Monterey Bay drainage system and have had an effect on the sediment yields from these basins:

1. Extensive urban development has decreased vegetative cover and, therefore, increased runoff and sediment input into the bay. Brown (1973) suggested that perhaps 80% of the increase is associated with road construction.

2. Logging practices in the San Lorenzo basin significantly increased siltation rates and altered the natural surface-water flow in the basin because great volumes of forest debris were left in the various tributaries of the drainage basin (Calif. Water Resources, 1966). Since 1960, better logging practices have lessened the severity of this problem.

3. Extensive agricultural development has increased siltation rates and altered the natural surface stream flow. The primary economy of both the Pajaro and Salinas basins is agriculture. For 1975, in the Salinas Valley alone, more than 809 km^2 (200,000 acres) were irrigated and about 200 km^2 (50,000 acres) were dry farmed (Irwin, 1976).

4. Reservoir construction has dramatically reduced surface stream flow in the Salinas basin.

3.11 Table 3-1 lists the reservoirs in all three basins. The Salinas basin reservoirs, located in the upper reaches of the basin, are an order of magnitude larger than any reservoir in the San Lorenzo or Pajaro basins and have drastically reduced stream discharge from the Salinas River. Average discharge at the Spreckels gaging station, approximately 18 km upstream from the mouth, was 349,611 acre-ft* from 1930 to 1956 but only 231,372 acre-ft between 1957 and 1972 (Arnal and others, 1973); the Nacimiento Dam was built in 1957. The small reservoirs in the Pajaro and San Lorenzo basins have not significantly reduced the average discharge.

3.12. It should also be noted that extensive sand and gravel mining occurs in the Santa Margarita formation in the San Lorenzo basin. This mining has been reported not to alter siltation rates in the stream system (Calif. Water Resources, 1966); however, the long-term impact of the sand and gravel mining on the basin's sand-sized sediment load has not been studied.

Sediment Charasteristics

3.13. Comparing grain size, sorting, and overall lithologic composition of the medium- to coarse-grained sands from the Salinas, Pajaro, and San Lorenzo Rivers and from Monterey Bay beaches helps to show the significance of each river as a potential source of beach sediment. Although it is difficult to use an overall lithologic composition to determine sand sources, the ultimate source of beach sediments can often be determined using diagnostic heavy minerals (see also the *Littoral-Zone Geomorphology* Chapter).

* An acre-foot is defined as the amount of liquid required to fill one acre to the depth of 1 foot.
acre-feet = (0.001233) cubic hectometers

Drainage Basin	Usable Capacity (acre-feet)	Use	Date Constructed
Salinas			
Santa Margarita Lake (near Pozo)	23,000	water supply for San Luis Obispo Co.	1941
Lake Nacimiento (near Bradley)	340,000	flood control irrigation	1957
Lake San Antonio (near Bradley)	330,000	flood control irrigation	1965
Parajo			
Chesbro Reservoir (near Morgan Hill)	8,090	flood control irrigation	1955
Uvas Reservoir (near Uvas Grant)	10,000	irrigation, ground water recharge	1957
San Lorenzo			
Loch Lomond	8,400	water supply for Santa Cruz Co.	1961

Table 3-1 Reservoirs of the Monterey Bay Drainage System (Usable Capacity, Use, Date Constructed)

GRAIN TEXTURE

3.14 Table 3-2 incorporates mean grain-size and sorting data from two separate studies (Yancey, 1968; Combellick, 1976). The mean grain-size data indicates that the San Lorenzo (0.22-0.24 mm) and Pajaro (0.24 mm) Rivers may be significant sources of sand for the northern beaches (0.24 mm). The Salinas River (0.17 mm, closest to the mouth) is generally not a significant source of sand for the southern beaches (0.55 mm). The Salinas River samples decrease in mean grain size downstream, indicating that medium to coarse sands are generally deposited upstream and do not reach the coast; however, they may be delivered to the coast during storms and periods of high runoff.

MINERALOGY

Overall Lithology

3.15. The average lithologic composition of the more common medium- to coarse-grained river and beach sands, listed in table 3-3, indicates that the San Lorenzo and Pajaro Rivers (more notably the San Lorenzo) are significant sources of sand for the northern beaches. The most common constituent on the northern beaches, undulatory quartz (41%), is the most common constituent in the San Lorenzo (45%) and the Pajaro (23%) Rivers. Just as the mean grain-size data suggested, the lower Salinas River is not a significant source of sand for the southern beaches. Undulatory quartz, again the most common constituent on the southern beaches (41%), makes up only six percent of the medium to coarse-grained Salinas River sand near its

Sample Location	Mean Grain Size (mm)	Mean Grain Size (phi)	Sorting Coefficient
San Lorenzo River	0.25	1.94-2.11	0.51
Pajaro River	0.29	1.78-1.80	0.32
Pajaro River	0.22	2.15-2.20	0.30
Salinas River			
6 km upstream	0.17	2.60	0.50
15 km upstream	0.48	1.10	1.10
32 km upstream	0.36	1.40	0.70
100 km upstream	0.80	0.30	1.40
Northern beaches	0.29	1.80	0.50
Southern beaches	0.58	0.80	0.70

Table 3-2. Mean grain size and sorting of river and beach samples in the Monterey Bay drainage system [*from* Combellick, 1976 and Yancey, 1968]

mouth. Salinas River samples taken further upstream are mineralogically, quite similar to southern beach sands. Therefore, the Salinas River may be a significant source of beach sand during storms and high runoff when sediments from upstream are transported to the coast (Combellick and Osborne, 1977).

Heavy Minerals

3.16. Figure 3-4 shows the average percentage of heavy-mineral concentrations for the heavy-mineral fraction of each of the three rivers (Yancey, 1968). Hornblende, augite, hypersthene, and garnet make-up at least 85% of the heavy mineral-fraction for the beach sands (Sayles, 1966); and, as figure 3-4 illustrates, these same minerals make-up at least 85% of the heavy mineral-fraction for the river sands. The Pajaro River contains diagnostic minerals, glaucophane and lawsonite, which, if found in the littoral zone, could possibly be assigned to it. The inland source of these two minerals is the Franciscan Formation, which is nearly restricted to the Pajaro basin (Yancey, 1968). However, Yancey's data also indicates that the Pliocene seacliffs in the northern part of the bay contain a small amount (0-2%) of glaucophane and lawsonite (see fig. 4-3). Therefore, the seacliffs cannot be discounted as a possible source.

3.17. Both the San Lorenzo and Salinas Rivers contain a relatively high percentage of garnet. Because sediment transport onto the southern beaches is restricted by the Monterey Canyon to the north and the Monterey Peninsula to the south, the inland source of garnet on the southern beaches is restricted to the Pliocene deposits (hornblende-garnet suite) of the upper Salinas Valley (Y ey, 1968). Garnet on the northern beaches, however, may have come from either the San Lorenzo River or may have been transported south, around Point Santa Cruz, by longshore transport. Garnet is much less abundant in the coastal cliffs in the northern part of the bay than it is in the San Lorenzo River (see fig. 4-3). This eliminates the cliffs as a significant source of garnet on the northern beaches.

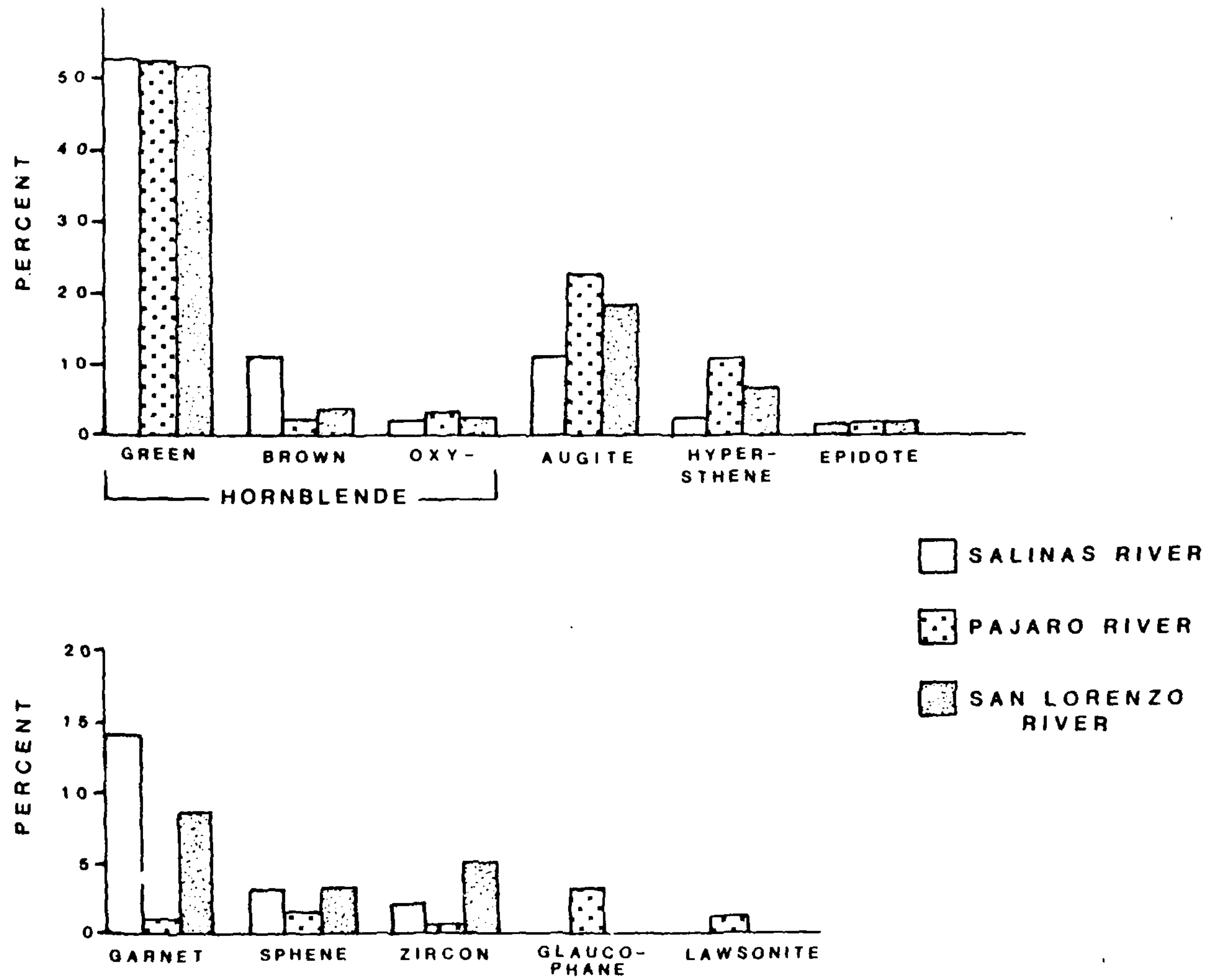


Figure 3-4. Average percent heavy-mineral concentrations for the heavy-mineral fraction of the Salinas, Pajaro, and San Lorenzo Rivers (*from* Yancey, 1968)

Constituents	Southern beaches	Northern beaches	Salinas River (dist. upstream)				Pajaro River	San Lorenzo River
			6 km	15 km	32 km	100 km		
MONOCRYSTALLINE GRAINS								
Non-undulatory quartz	2	4	tr	2	1	1	1	2
Undulatory quartz	41	41	6	40	37	36	23	45
K-feldspar	17	10	6	15	9	15	9	19
Plagioclase	12	11	4	12	17	17	12	9
Accessory minerals	2	1	60*	3	2	tr	3	tr
Unidentified minerals	2	1	5	1	3	2	2	1
ROCK FRAGMENTS								
Granite	9	5	2	8	10	9	6	13
Plutonic quartz	7	5	2	7	7	7	8	5
Metamorphic quartz	tr	1		1	tr		1	
Orthoquartzite	1	2	-	2	tr	-	1	tr
Arkose, subarkose	1	tr	-	2	1	tr	1	tr
Graywacke	tr	1		tr	-	1	3	
Siltstone	1	3	1	1	3	5	4	1
Shale	tr	2	1	1	1	1	2	tr
Chert	2	4	5	1	1	2	4	1
Felsite	tr	3	tr	tr	1		5	
Unidentified	3	7	8	4	7	4	14	3
Shell material	tr	tr	tr			tr		
Avg. % represented by 0.35-0.50 mm fraction	14	13	1	22	37	27	2	26

* Nearly all biotite   tr = trace

Table 3-3. Average percent lithologic composition of the 0.35 to 0.50 mm size fraction of river and beach samples in the Monterey Bay drainage system [from Combellick and Osborne, 1977]

3.18. All the other heavy minerals discussed are common to all three rivers, and littoral transport and mixing with other sediments would alter the proportions of each mineral, making it impossible to site an ultimate source area. Cliff and dune erosion cannot be discounted as a possible source of heavy minerals as well. Also, the heavy-mineral fraction on the Monterey Bay beaches is fine-grained and only constitutes a small fraction of the littoral-zone sediments in most areas (Hutton, 1959); therefore, the identification of the heavy-mineral provenance does not necessarily explain the provenance of the more common medium- to coarse-grained sand in Monterey Bay (Yancey, 1968).

SAND SOURCES

3.19 Although ultimate sand sources cannot be quantitatively determined for the majority of the beach sands, the regional geology of the Monterey Bay drainage system indicates that several rock units can be qualitatively regarded as important ultimate sand sources (see Stratigraphy section of *Neotectonics* Chapter for detailed rock descriptions). This is based on the rock unit's geographic distribution, erodibility, and potential to produce medium- to coarse-grained sediments (Greene, 1978; Yancey, 1968).

3.20. The Cretaceous Santa Lucia granodiorite and siliceous shales of the Tertiary Monterey formation are the most important pre-Quaternary sources of Salinas River sand. Extensive Quaternary deposits along stream beds (alluvium, sand dunes, and terrace deposits) are also important sources. Pre-Quaternary sources of Pajaro River sediments almost exclusively outcrop east of the Pajaro Gap. These rock units include minor amounts of granitic basement rock, metamorphic and sedimentary rocks of the Franciscan Formation, and extensive outcrops of the Tertiary Purisima formation. Extensive Quaternary sand sources crop out along the river channel west of the gap. Most notable are the Aromas sandstone, alluvium, and terrace deposits. Most sediments in the San Lorenzo River come from pre-Quaternary rocks in the Santa Cruz Mountains. Most notable are the Cretaceous granodiorites and the Tertiary Monterey, Santa Margarita and Purisima formations. Quaternary alluvium, although not geographically widespread in the San Lorenzo basin, inputs appreciable amounts of sediment due to landsliding (Nolan and others, 1984).

Sediment Yields

3.21 Several approaches have been used to estimate the average volume of sand delivered to Monterey Bay by rivers. Arnal and others (1973) calculated sediment yield from stream gage and precipitation data, and also estimated sediment yield per km^2 based on similar studies of the Santa Maria and Santa Inez Rivers. Dittmer (1972) presented sediment yields for the bay predominantly based on discharge data from 1971-1972. Dorman (1968) calculated sediment yields, for the Salinas River only, by measuring the growth rate of the Salinas River delta and using stream-discharge and suspended-sediment data. Based on previous studies, Welday (1972) presented sediment yields for the Salinas River. Hicks (1985) presented average sediment yields for the San Lorenzo River and calculated the volume of sediment delivered to the coast during the high energy storms of 1982 and 1983. Table 3-4 lists the sediment yields generated by these studies.

3.22. At least three factors contribute to the very wide range of sediment-load estimates for Monterey Bay. First, it is difficult, at best, to calculate sediment yields using discharge data, as done by Arnal and others, and Dorman. As stated by Guy (1964):

> Sediment transport in a stream depends on such a great variety of circumstances that it is not considered practical to define fixed laws that would indicate the rate and amount of such sediment transport in the stream at any specific location. More specifically, the effects of widely varying climate, vegetation, and soils cause sediment conditions in streams to vary widely in time and space. Therefore, the task of describing and interpreting the yield, character, transport, and deposition of fluvial sediment seems almost insurmountable.

Although the equations and models for calculating sediment yields from streams have been improved since this 1964 quote (Burkham and Dawdy, 1980), they are far from perfect and leave a wide margin of error. There are watershed models being developed at this time; however, no real good ones exist, especially for steep terrained basins, like the San Lorenzo, where landsliding

Sediment Yield (m^3)

Author Method	Salinas River	Pajaro River	San Lorenzo River	Total Bay Sediment Load
Arnal and others Stream flow data				
(pre-1957)	439,000			746,000
(post 1957)	285,000	136,000	179,000	600,000
Arnal and others sediment/km^2	483,000	272,800	37,500	786,100
Arnal and others precipitation data				917,000
Arnal and others final average				
(pre-1957)				765-917,000
(post-1957)				612,000
Dorman delta growth	765,000			
Dorman stream gage data (1965-1967)	19,000			
Dorman susp. sed. data (1966-1967)	229,000 (incl. silt)			
Dittmer estimates from previous work and 1971-1972 data	229,000	153-382,000	28,000	306-382,000
Welday estimates from previous work (pre-1957)	382-765,000			
Welday				
med. to coarse sand	30,000			
total river discharge (post-1957)	305,000			
Hicks (littoral load only)				
1972-1981			16,400	
1981-1982			45,600	
1982-1983			175,300	

Table 3-4. Sediment yields for the Salinas, Pajaro, and San Lorenzo Rivers (*in* m^3)

is so prevalent (oral comm. M. Nolan, 1985). Second several of the studies (portions of Arnal and others, Dittmer, and Welday) did not quantify their size limit for "total sediment". Arnal and others and Dittmer do refer to their sediment yield figures as total sand, but they do not clearly define "sand". Welday quantifies his size limits in only one of his two estimates. These unquantified figures may represent the total sediment load, which includes clay, silt, and sand; total sand load, in which case sand should be defined ; or total littoral sand, which is 0.23 mm to 0.70 mm for Monterey Bay (Yancey, 1968). Several of the reports do quantify what they mean by sediment yield. Dorman calls his sediment yield total sand, and he defines sand as ranging between 4 phi and -1 phi and Hicks defines his sediment yield as littoral load only. Third, Dittmer's estimate (and one of Dorman's estimates) is based on only one year of data, and sediment yields for these rivers vary dramatically from year to year. Nolan and others (1984) reported that the three-day storm of January 3-5, 1982 input 4.1 times the average annual sediment yield for the period 1973-1980 on the San Lorenzo River, and Hicks (1985) reported that approximately 70% of the littoral load from 1972-1983 was delivered between 1982-1983. Figure 3-5, compiled from U.S.G.S. suspended-sediment data on the Salinas River at Spreckels, demonstrates that the infrequent, large storms deliver the bulk of the sediment from the rivers to the littoral zone (Hicks, 1985). Figure 3-5 does not include bedload volume and the total suspended sediment load in the rivers is much greater than that which remains in the littoral zone. Therefore, figure 3-5 cannot be used to estimate an absolute volume of beach-size sediment; however, it does indicate the relative magnitudes and frequencies of littoral sediment-supply events. Variation in storm duration and greater-than-normal antecedent precipitation will also alter the amount of sediment produced during high stream discharge (Blodgett and Poeschel, 1984), which makes it even more difficult to predict sediment yields from a given storm event using stream-discharge data. However, in general, sediment input from rivers occurs in large infrequent pulses, often creating ephemeral river deltas, and one must be cautious when using annual suspended-sediment averages to estimate sediment yields.

3.23. Although the estimates for each river vary between the studies, and any average annual sediment discharge or computation of sediment discharge using stream-discharge data can be misleading, table 3-4 indicates that the average annual total sand contribution, (defined as 0.0625 mm to 2 mm), from all three basins into Monterey Bay is roughly 300,000 to 600,000 m^3/yr.

Summary

3.24. The total sand yield (.0625 mm - 2 mm) from the drainage basins to Monterey Bay is roughly 300,000 to 600,000 m^3/yr; however, the Monterey Bay littoral zone is composed of medium to coarse sand (0.29 mm - 0.58 mm). Although difficult to estimate, 60-75% of the total sediment load may be carried offshore, and the percentage may reach as high as 90% in the southern part of the bay where the average littoral-zone sediments are coarse grained (Welday, 1972).

3.25. Comparing the grain size and sorting of the river sands with that of the beach sands indicates that the rivers are a major source of the medium- to coarse-grained beach sands (0.29 mm - 0.58 mm) on the northern beaches, but only a major source on the southern beaches during storms and high runoff. Also, lithologic composition of the 0.35 to 0.50 mm fraction in the river samples differs from the same fraction in the beach samples in the southern part of the bay (Combellick, 1976; Combellick and Osborne, 1977). The fine-grained heavy-mineral fraction in the littoral-zone sediments can often be traced to the Salinas and Pajaro basins; however, the San Lorenzo basin heavy minerals, once incorporated into the littoral zone, do not exhibit a detectable mineral provenance. Coastal cliffs and transport from outside the study area cannot be discounted as a source area for the heavy minerals, and the identification of any heavy-mineral provenance still does not explain the provenance of the more common medium to coarse

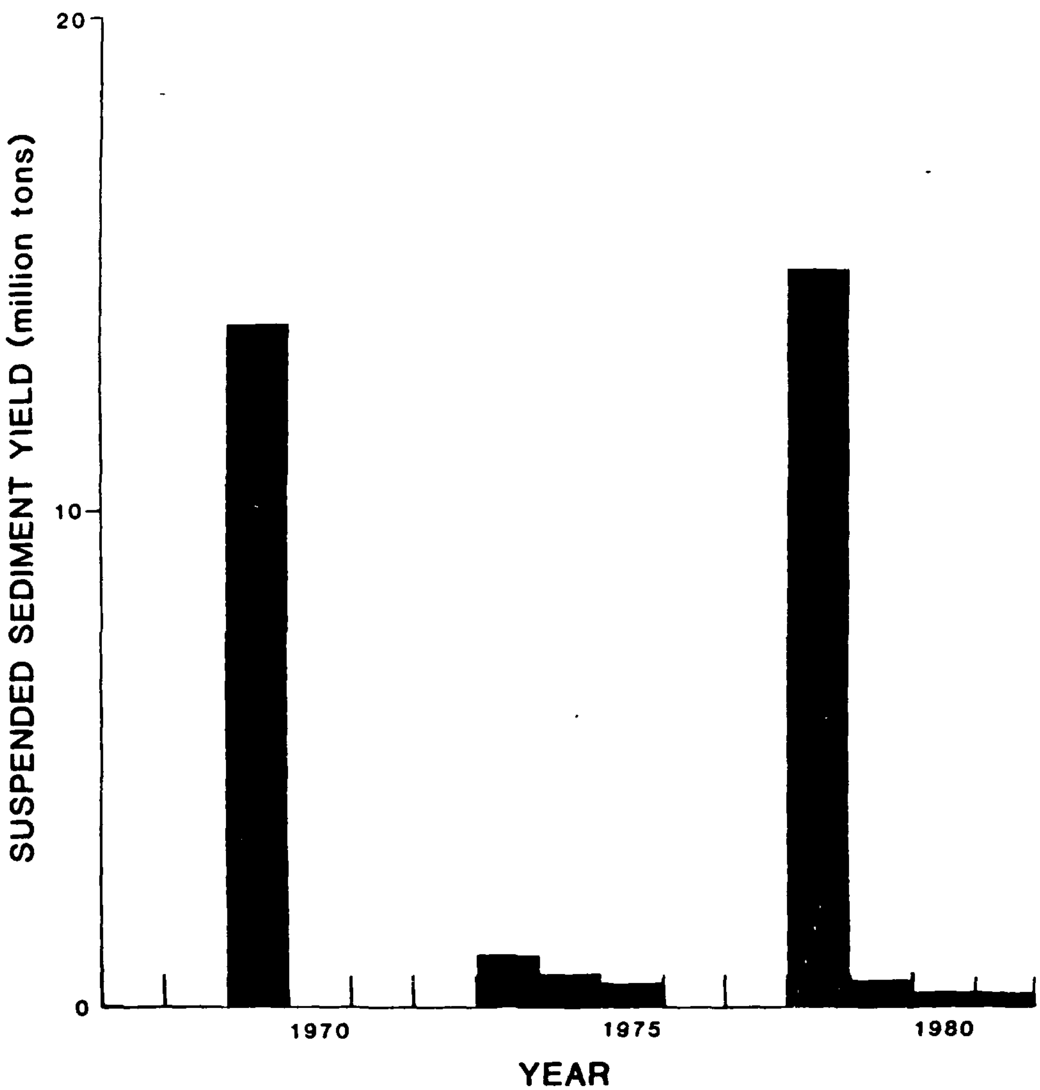


Figure 3-5. Suspended-sediment yield on the Salinas River at Spreckels, 1967-1981 [*from* Hicks, 1985]

sand. Examination of the complex regional geology in the Monterey Bay drainage system does reveal several rock units that should qualitatively be regarded as important original sand sources; however, at this time the littoral-size sediment yields from these rock units have not been determined.

4. COASTAL CLIFF RESOURCES

4.1. The coastal cliff resources in Monterey Bay can be divided into two types: the seacliffs fronting the north bay marine terraces that extend for approximately 15 km from Point Santa Cruz to La Selva Beach, and the bluffs on the seaward edge of the central and south bay Flandrian and pre-Flandrian dune belt that extend for approximately 23 km from La Selva Beach to Del Monte Beach (fig. 4-1). This chapter will first discuss the north-bay marine terraces and will then discuss the central- and south-bay Flandrian and pre-Flandrian dune belt.

North Bay

CLIFF DISTRIBUTION

4.2. The seacliffs from Point Santa Cruz to La Selva Beach, which range in height from about 6 to 36 m, are uplifted marine terraces (Griggs and Johnson, 1983). The cliffs are fronted by wide sandy beaches from just north of the Santa Cruz Municipal Pier to the Santa Cruz Harbor and by sandy pocket beaches from that harbor to Soquel Point. Exposed wave-cut cliffs extend continuously from Soquel Point to New Brighton Beach, excluding several small pocket beaches and the wide sandy beach at the mouth of Soquel Creek. From New Brighton to La Selva Beach, the cliffs are fronted by a continuous sandy beach, which widens to the south. Figure 4-2 illustrates not only the cliff distribution, but also the shoreline condition, that is, whether or not the cliffs are artificially protected. The presence of any artificial protection will, The presence of any artificial protection will, of course, decrease the yield of sand-sized sediments from the cliffs to the littoral zone.

4.3. The seacliffs are composed of three sedimentary rock types: the Mio-Pliocene Santa Cruz Mudstone, the Pliocene Purisima Formation (siltstone and sandstone), and the Quaternary Aromas Sandstone. These sedimentary rocks are usually capped by 1.5 to 6.0 m of unconsolidated marine and non-marine Quaternary terrace deposits (Griggs and Johnson, 1979).

4.4. The Santa Cruz Mudstone outcrops in the seacliffs north of the Santa Cruz Harbor and in the shore platforms scattered from Point Santa Cruz to Capitola. The Purisima Formation, which overlies the Santa Cruz Mudstone, is exposed from Point Santa Cruz to just south of Rio del Mar, and the Aromas Sandstone is exposed from approximately Rio del Mar to La Selva. Plate 1 details the local geology.

SEDIMENT CHARACTERISTICS

4.5. Comparing grain size, overall lithologic composition, and heavy-mineral composition from the three sedimentary rock units and the Quaternary deposits, and those sands found on the beaches helps to show the significance of the cliff deposits as a potential source of littoral sediments.

Sediment Texture

4.6. The grain-size distribution within the three sedimentary rock formations and the terrace

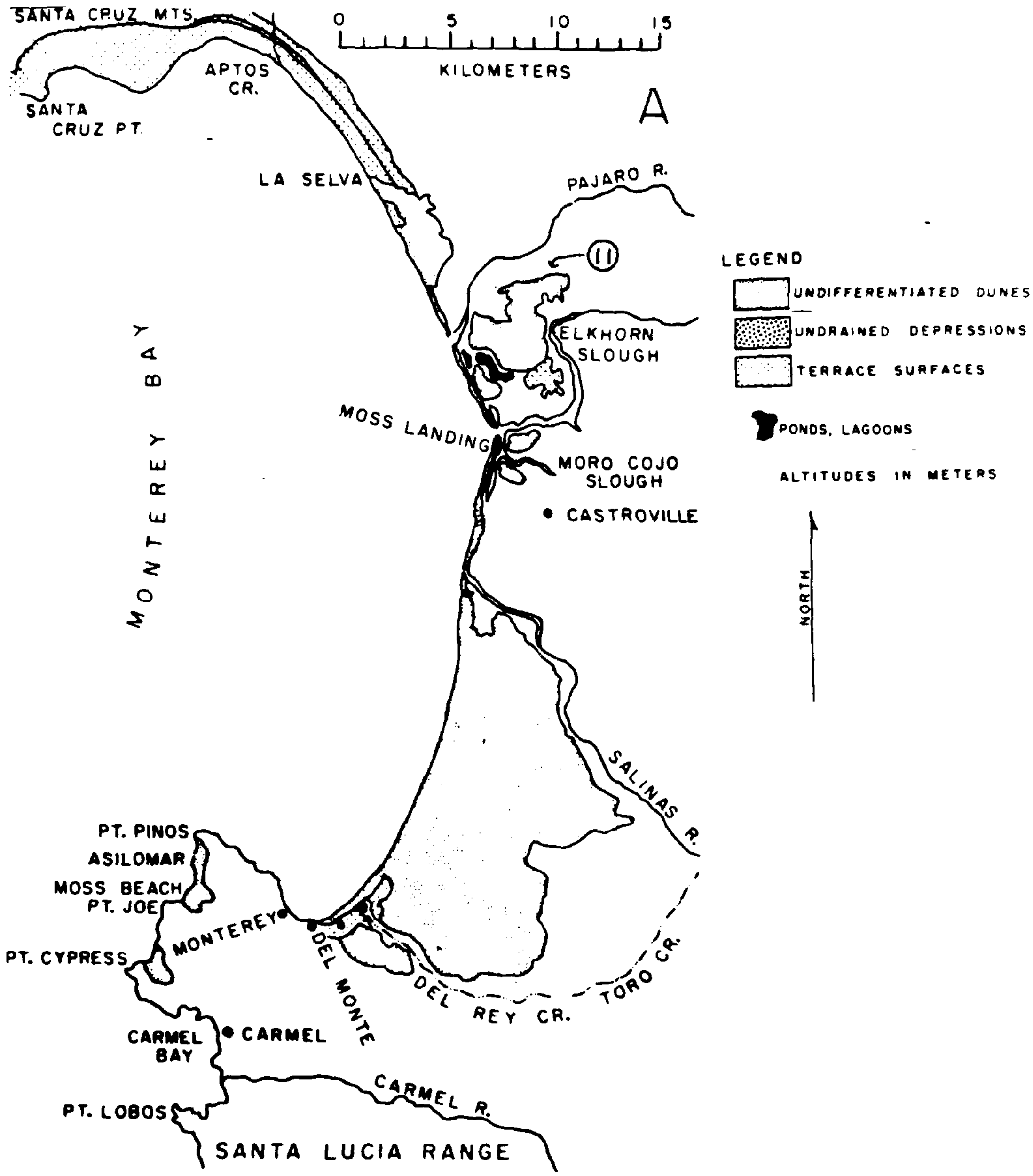


Figure 4-1. Cliff and dune distribution in Monterey Bay [*from* Cooper, 1967]

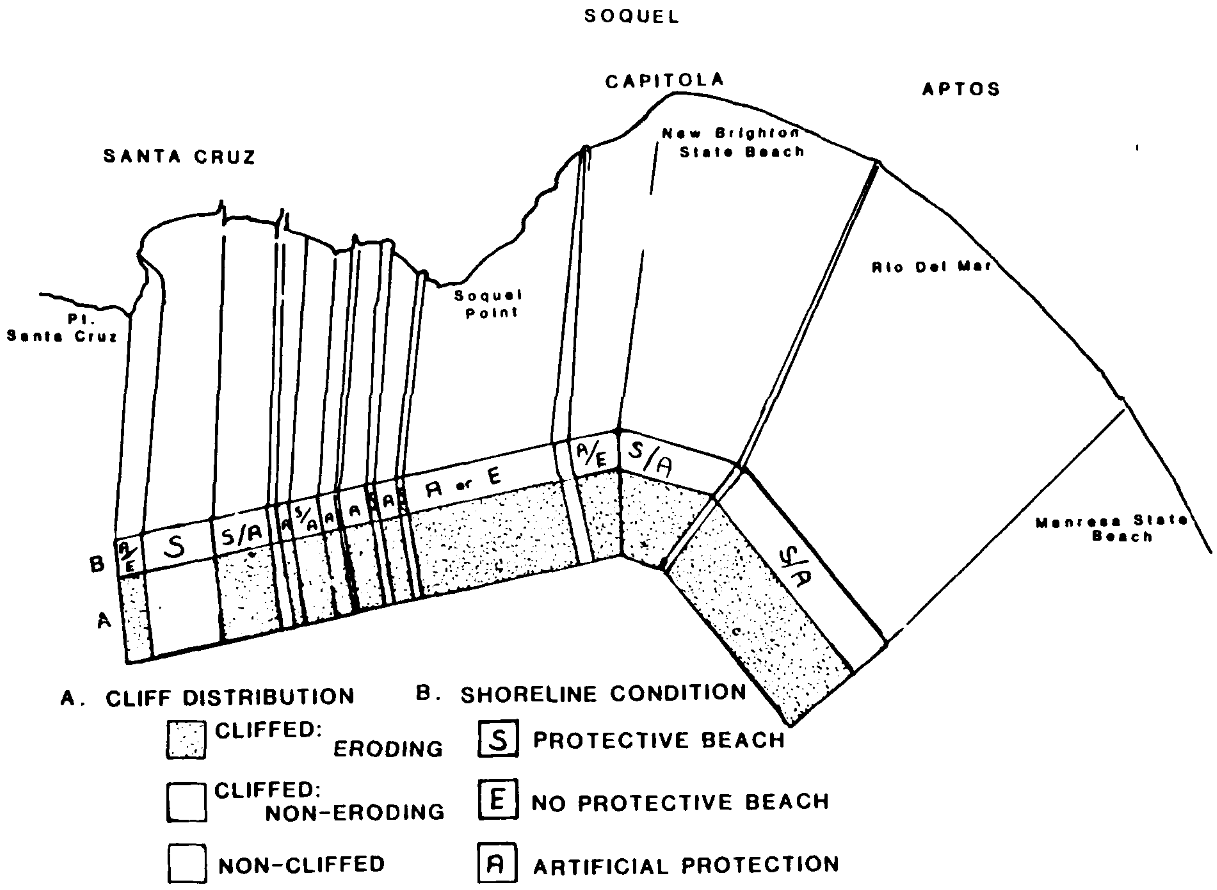


Figure 4-2. Cliff distribution and shoreline condition, Point Santa Cruz to Manresa State Beach [*from* Dept. of Nav. and Ocean Dev., 1977]

deposits must be considered to determine the percentage of littoral-size * sediments in each unit. Figure 4-3 is a log-normal plot of grain-size distributions from individual sediment samples in the Monterey Bay cliff deposits (Yancey, 1968). Beach-size sediments for northern Monterey Bay have been reported to have an average grain size of 0.29 mm (Combellick and Osborne, 1977). The Santa Cruz Mudstone, 99.5% finer than 0.29 mm, is obviously not a potential source of beach sediment. Both the Purisima Formation and the Aromas Sandstone contain beds with approximately 99.5% of the sediment finer than 0.29 mm; however, they also contain beds with 52-74% sand that is 0.29 mm or coarser. Most of the Aromas and much of the Purisima are sand beds and, therefore, these two formations are significant sources of littoral-size sand. The Quaternary terrace deposit sampled by Yancey contained 54% sand 0.29 mm or coarser. These terrace sediments are mostly medium- to coarse-grained prograding beach deposits; however, there are areas of Quaternary alluvial deposits that may not contain as much medium-to-coarse sand. These individual samples can be used to describe the approximate grain size of the coastal cliff deposits; however, they cannot be used to accurately quantify just how much beach sand each unit contributes. It would be necessary to sample and analyze the cliff deposits in several locations to calculate the average percentage of littoral-size sediments contained in each member of the three formations.

Mineralogy

4.7. **Overall Lithology:** Grain-size data indicate that portions of the Purisima Formation, Aromas Sandstone, and Quaternary terrace deposits contribute sediment to the littoral zone. Table 4-1 lists the overall lithologic composition for the Purisima Formation (marine and non-marine members), the Aromas Sandstone, and the beach sands for the northern bay (Davis and Henderson, 1957; Combellick, 1976). There is no available data for the Quaternary terrace deposits. These data sets indicate that the Purisima Formation and the Aromas Sandstone are mineralogically similar to the northern beach sands. Combellick's data is especially significant not only because his breakdown is more specific, but also because he notes the average percentage represented by the 0.35-0.50 mm fraction. The Aromas Sandstone (12%) and the northern beach sands (13%) contain almost the same percentage of 0.35-0.50 mm sand.

4.8. **Heavy Minerals:** Figure 4-4 shows the average composition of the heavy mineral fraction in the Santa Cruz Mudstone, Purisima Formation, Aromas Sandstone, and Quaternary terrace deposits. Hornblende, augite, hypersthene, and garnet make-up at least 85% of the heavy-mineral fraction of the beach sands (Sayles, 1966) and, excluding garnet, these same minerals make-up at least 85% of the heavy-mineral fraction for the cliff sediments. This indicates that the relatively high percentage of garnet on the northern beaches most likely came from the San Lorenzo River or from outside the study area (see fig 3-4). The cliff sediments do not contain any other diagnostic minerals that, if found in the littoral zone, could be assigned to them, since all the minerals listed are also found in the river sands. However, the similar heavy-mineral composition suggests that the coastal cliffs are a significant source of at least the fine-grained heavy minerals.

CLIFF EROSION

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* littoral-size is limited to grain sizes found in the littoral zone

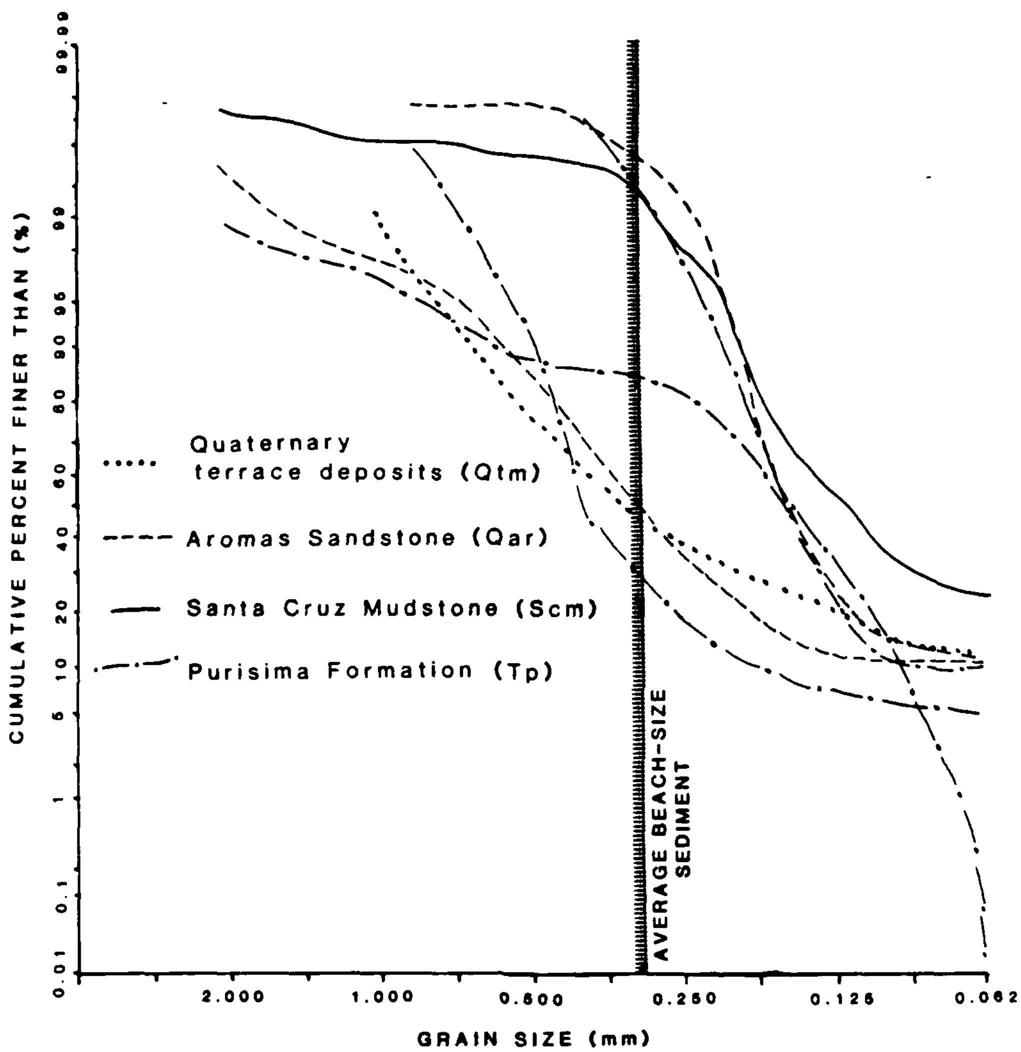


Figure 4-3. Grain-size distribution for the Santa Cruz Mudstone, Purisima Formation, Aromas Sandstone, and Quaternary terrace deposits [*from* Yancey, 1968]

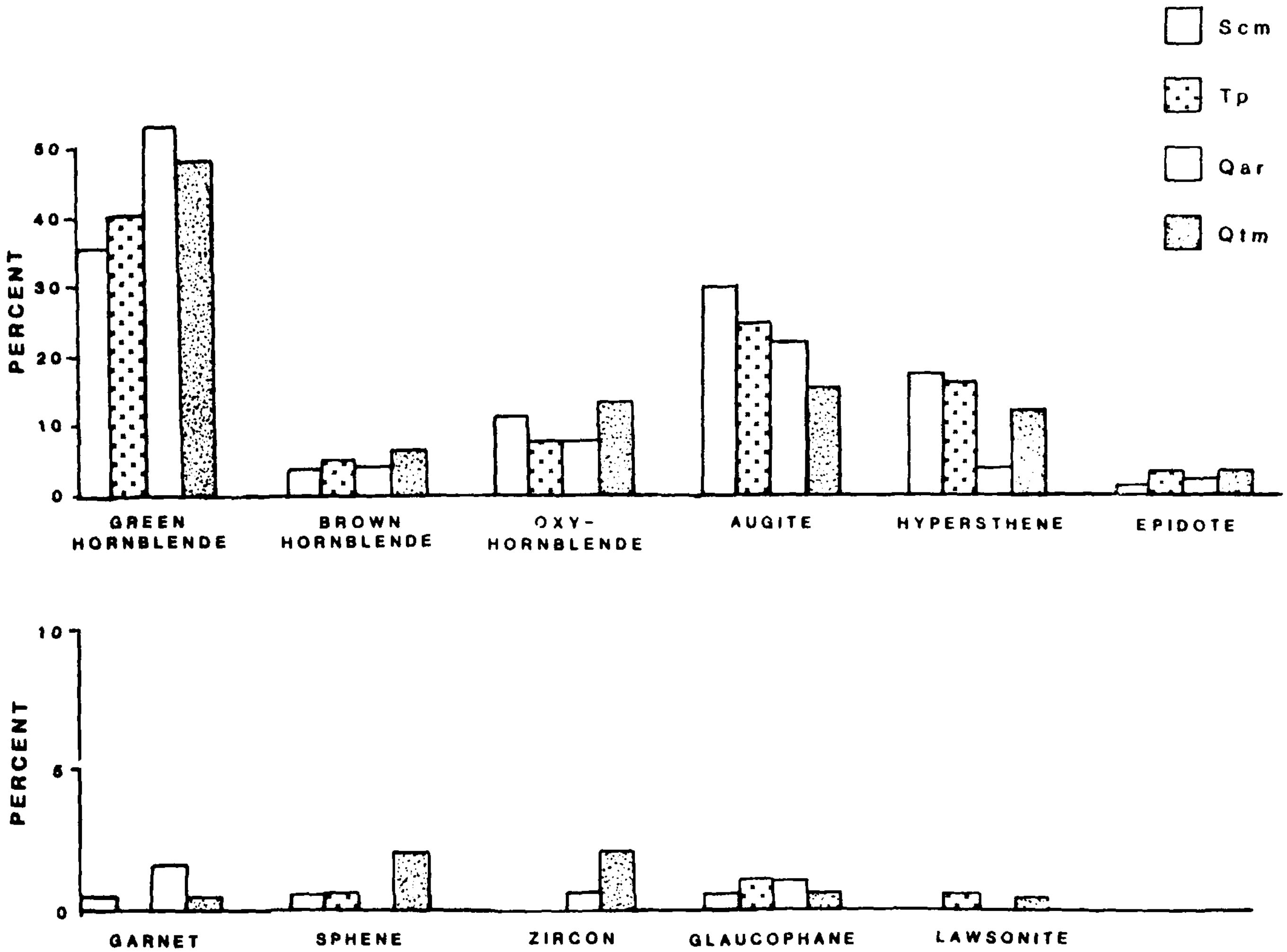


Figure 4-4. Average percentage heavy-mineral concentrations for the Santa Cruz Mudstone (Scm), Purisima Formation (Tp), Aromas Sandstone (Qar), and Quaternary terrace deposits (Qtm) [*from* Yancey, 1968]

	Davis & Henderson			Combellick	
Constituent	Marine Purisima	Non-Marine Purisima	Aromas Sandstone	Aromas Sandstone	Northern Beaches
Quartz	34-45	30-38	27-47		
Feldspar	25-35	27-31	20-37		
Lithic Fragments	10-20	20-23	10-25		
MONOCRYSTALLINE GRAINS					
Non-Undulatory Quartz				2	4
Undulatory Quartz				44	41
K-Feldspar				15	10
Plagioclase				12	11
Accessory Minerals				2	2
Unidentified Minerals				tr*	1
ROCK FRAGMENTS					
Granite				11	5
Plutonic Quartz				11	5
Metamorphic Quartz				-	1
Orthoquartzite				tr	2
Arkose, subarkose				tr	tr
Graywacke				-	1
Siltstone				tr	3
Shale				-	2
Chert				1	4
Felsite				-	3
Unidentified				1	7
Shell material				-	tr
Average % represented by 0.35 to 0.50 mm fraction				12	13

*tr = trace

Table 4-1. Average percentage lithologic composition of coastal cliffs and northern beach sands [*from* Davis and Henderson, 1957; Combellick, 1976]

Erosion Processes

4.9. Both terrestrial and marine processes cause cliff erosion. Terrestrial processes (high rains and run-off) generally cause gullying and, if no marine erosion is occurring, terrestrial erosion will leave a talus at the base of the seacliffs. Marine processes (high wave energy and unprotected cliff exposure) generally create a sharp angle at the base of the cliffs (fig. 4-5a). Variations in the lithologic composition of the seacliffs can, of course, create a wide array of cliff profiles. Figure 4-5b illustrates the variety of seacliff profiles one can expect with varying degrees of marine and terrestrial erosion and various cliff lithologies. Geologic structure (joints, faults, and folding) will also affect the seacliff profiles by creating zones of weakness where

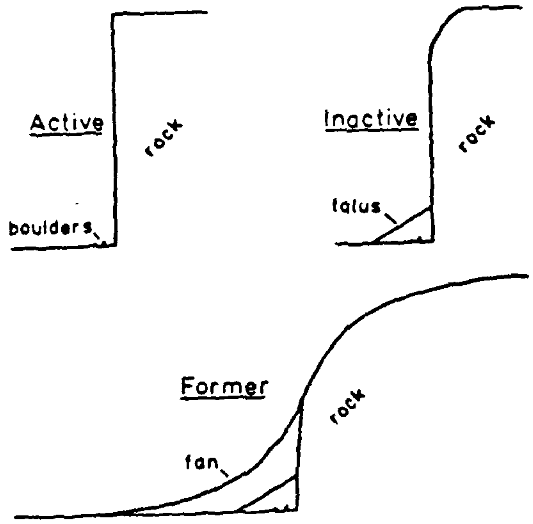


Figure 4-5a. Idealized stages in geological history of a sea cliff [from Emery and Kuhn, 1982]

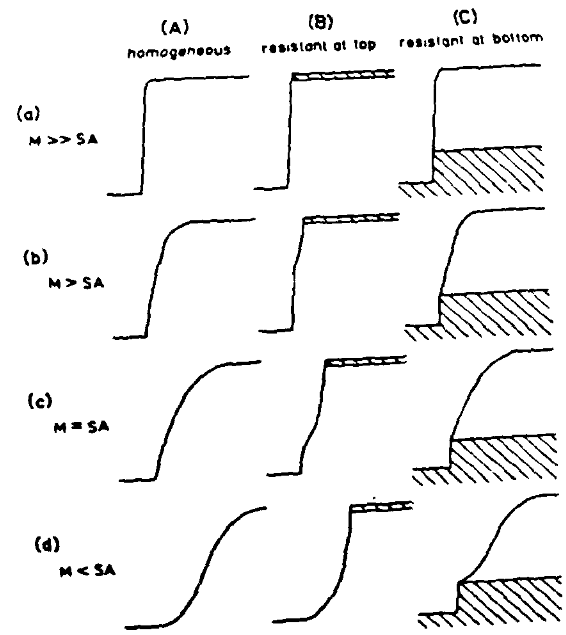


Figure 4-5b. Matrix of active seacliff profiles to be expected from three different bedrocks and four different major degrees of relative effectiveness of marine (M) versus subaerial (SA) erosion. It assumes that seacliffs are cut into plateaus and are near steady state equilibrium. Diagonal lines denote resistant beds. [from Emery and Kuhn, 1982]

erosion is accelerated and by juxtaposing different lithologic units, which have varying degrees of erosional resistance.

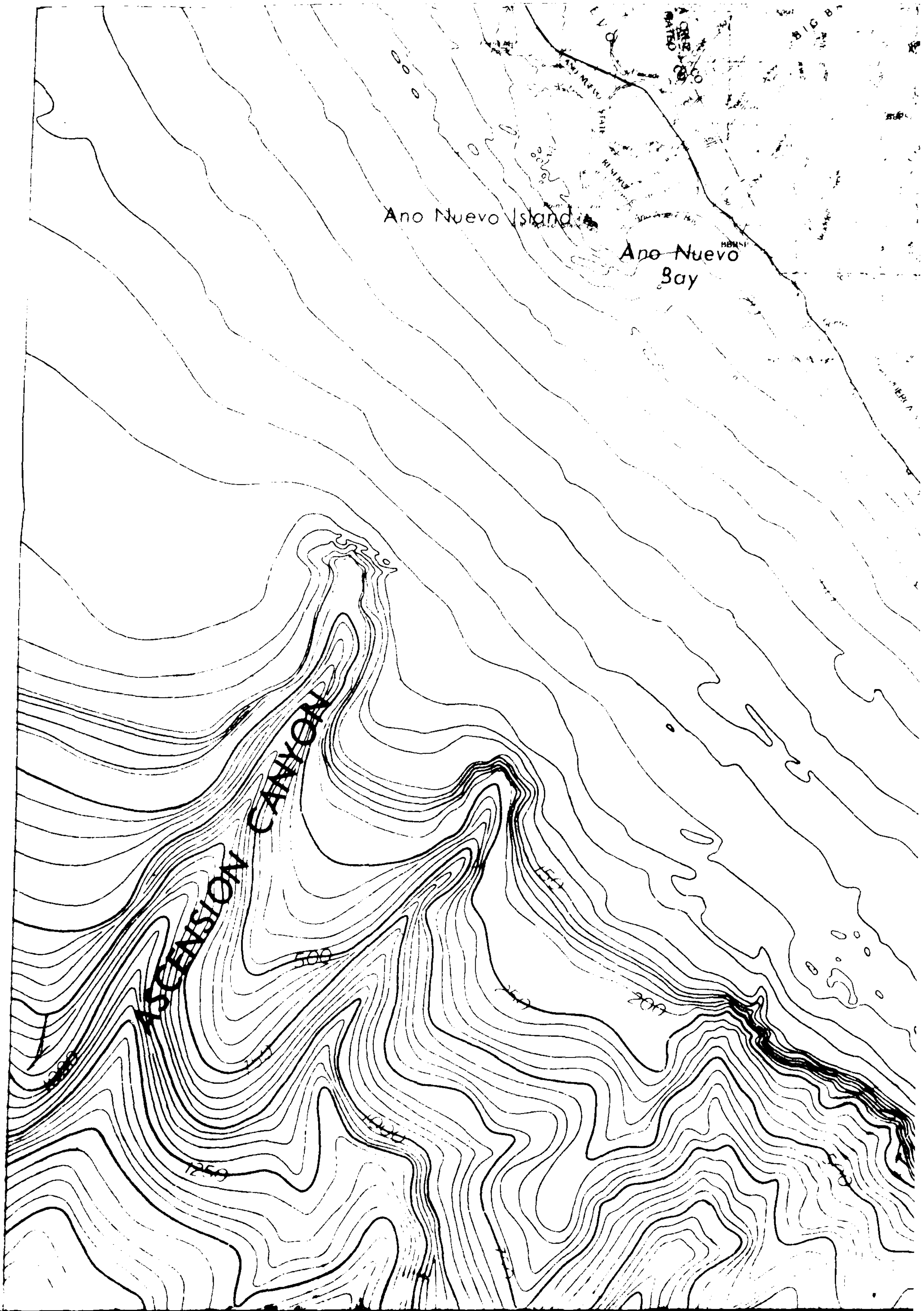
4.10. In northern Monterey Bay, seacliff erosion is predominantly a marine process although extensive gullying (up to 44 cm/yr) caused by terrestrial erosion does occur. The largest deep-water waves (4.5 m can be expected 5 times a year) are caused by winter storms and arrive in an arc between the northwest and southwest (Griggs and Johnson, 1979; see also *Littoral-Zone Resources* Chapter). The rate of seacliff erosion depends upon not only wave energy and cliff exposure, but also depends upon the lithologic composition, geologic structure, and height of the seacliffs.

4.11. Griggs and Johnson (1979, 1983) noted the following relationships between erosion characteristics and sea-cliff compositions in Santa Cruz County. The Santa Cruz Mudstone is, overall, highly resistant to erosion and its nearly flat-lying siliceous beds often create a shore platform. Sandstone beds and sandstone intrusions within the Santa Cruz Mudstone are less resistant to wave impact, creating arches, caves, and tunnels such as the arch at Natural Bridges State Park. The Purisima Formation, with its thinly- to thickly-bedded siltstones and sandstones and interbeds or lenses of mollusk shells, generally provides little resistance to wave attack. The Purisima is also highly jointed and often erodes in large blocks along joint sets. Block failure results in large-scale, episodic erosion and these blocks often serve as temporary rip-rap in areas where the cliffs are high and the resulting blocks are, therefore, quite large. The Aromas Sandstone is semiconsolidated and erodes very quickly. The Quaternary terrace deposits are unconsolidated and highly erodible.

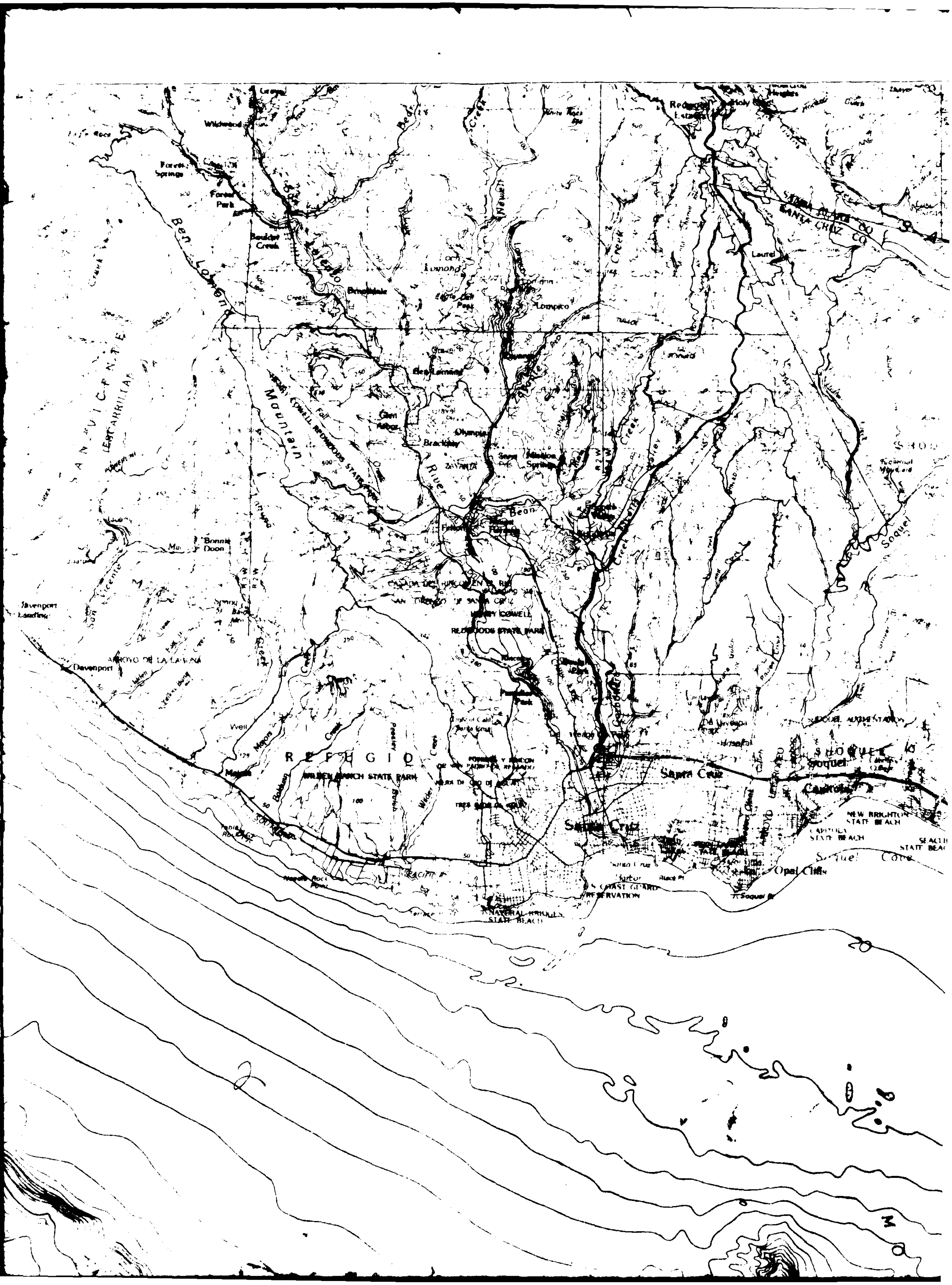
Historical Changes

4.12. Historical topographic maps, bathymetric charts, and aerial photographs have been used to calculate average historical rates of cliff erosion. Figures 4-6 and 4-7 (Griggs and Johnson, 1979) show the average rates of erosion from San Lorenzo Point to Capitola between 1850 and 1970. [from Griggs and Johnson, 1979] Erosion rates are highest where the cliffs are composed of mostly terrace deposits. Within the Purisima Formation, erosion rates are highest where the bedrock is faulted and, most likely, highly jointed. Erosion rates have been considerably reduced in many locations as a result of artificial protection. Eight of the 15.2 km of northern Monterey Bay coastline (53%) is now protected by rip-rap or seawalls (Griggs and Johnson, 1983). Also, between 1960 and 1970, the erosion rates increased dramatically in certain spots in the Capitola area, as compared to the average rates between 1850 and 1960. Erosion rates reached 88.4 cm/yr just east of Soquel Creek. This increased erosion rate in Capitola, in part, is due to a decrease in upcoast sources of littoral sand. Increased artificial protection along the cliffs west of Capitola and an interference of the natural littoral transport at the Santa Cruz Harbor may be the cause of these high rates of erosion (U.S. Army Corp of Engineers, 1969).

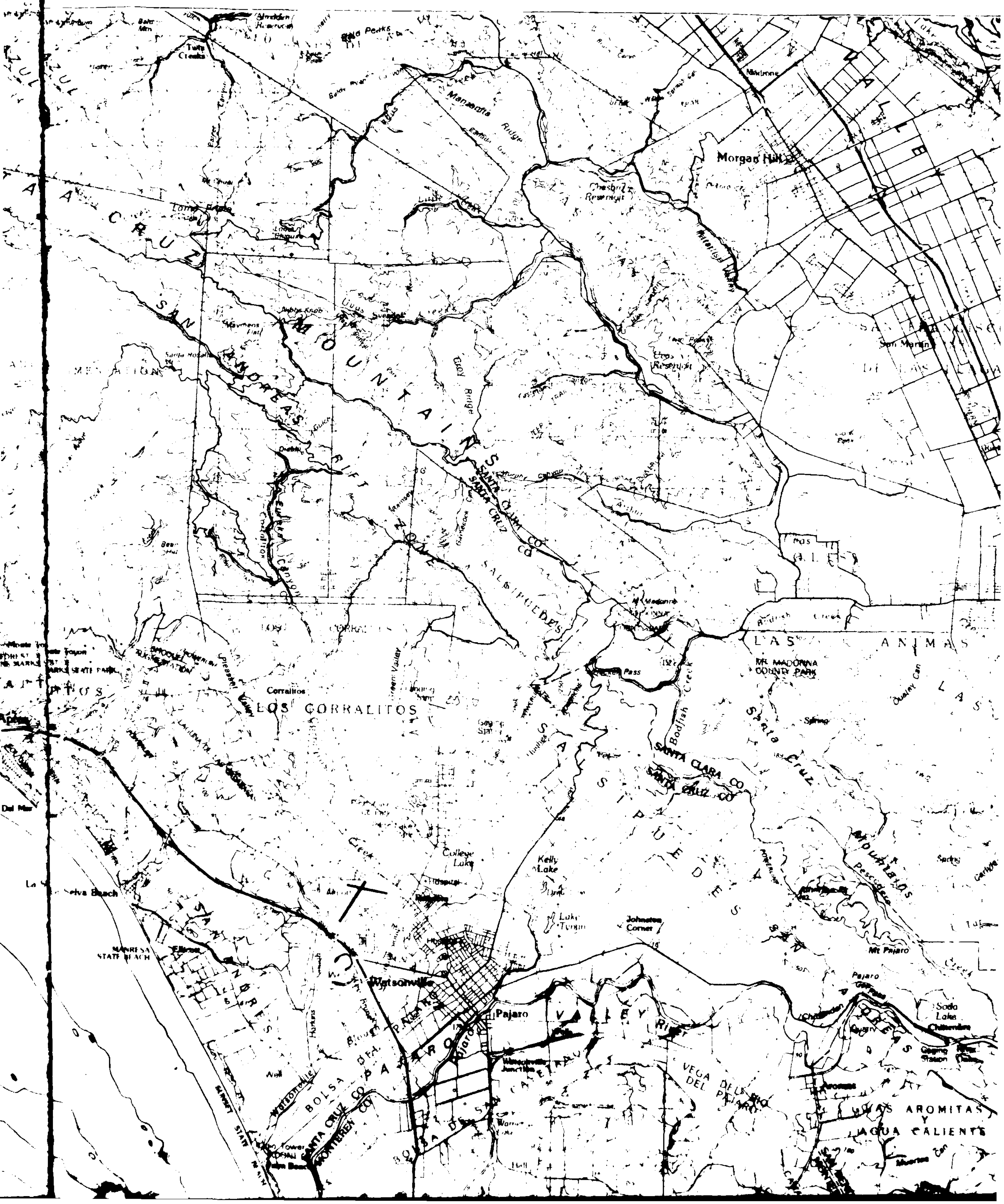
4.13. Weber (oral comm., 1985) has documented increased rates of erosion from New Brighton Beach to the mouth of the Pajaro River within the past 8-10 years. The steep, mostly unvegetated seacliffs in southern Santa Cruz County indicate extensive wave erosion during the past 3000-4000 years since sea level stabilized; however, historic rates of erosion during the past 100+ years (excluding the last 8-10 years) have been relatively minor. He suggests that the recent increased erosion rates in this area relate to a decrease in the volume of sediment available to the littoral zone. This sediment reduction is related to the following:



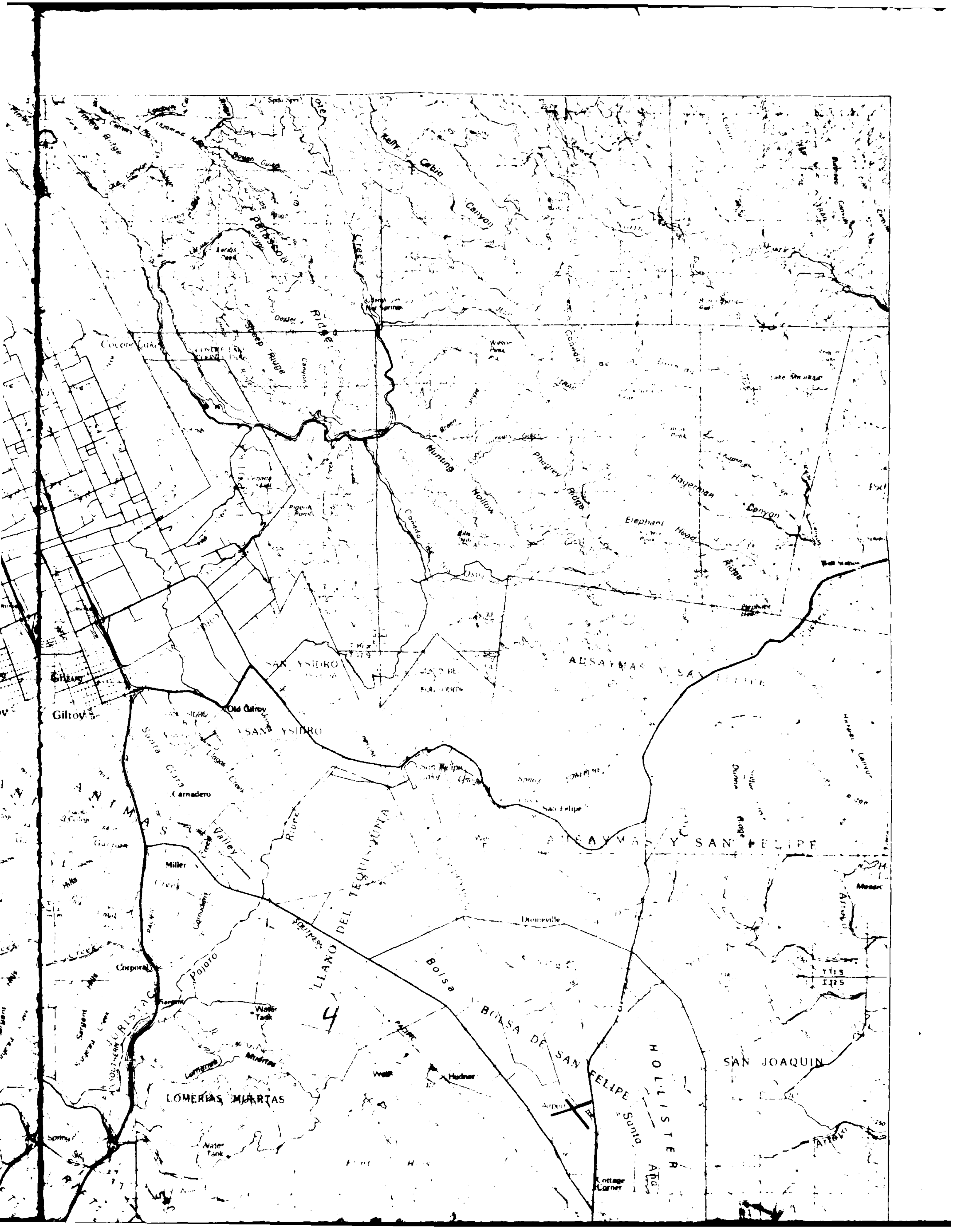
Ano Nuevo Island
Ano Nuevo Bay
ASCENSION CANYON
500
200
1250



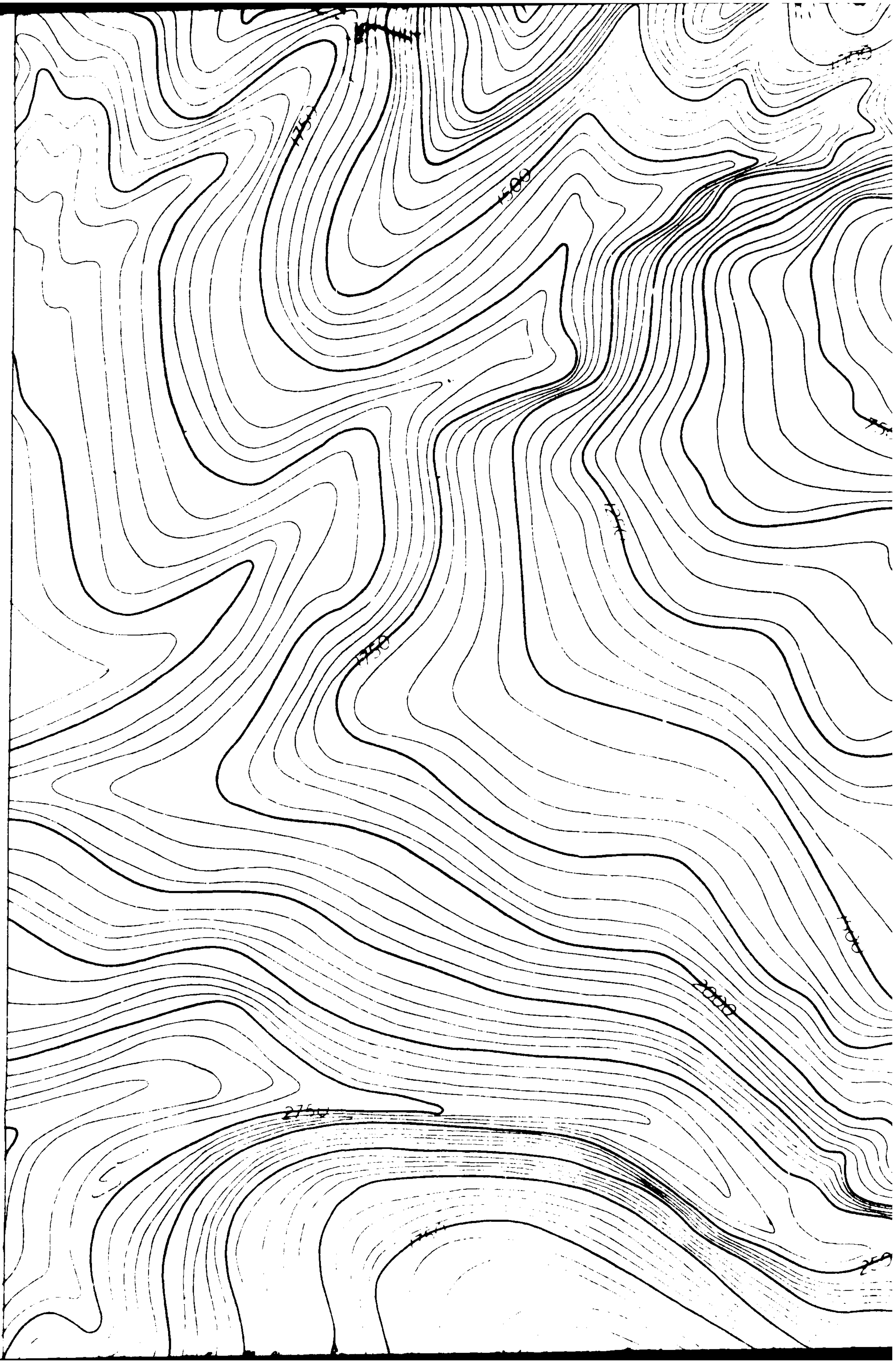
Boulder Creek
Forest Park
Wildwood
Brookdale
Lompico
Laurel
Redwood Estates
Holy City
SANTA CLARA CO
SANTA CRUZ CO
Ben Lomond
Mountain
Glen Arbor
Brackney
Olympia
Zayante
Mission Springs
River
Felton
Bonny Doon
Davenport Landing
Davenport
ARROYO DE LA LAGUNA
HENRY COWELL
REDWOODS STATE PARK
R E F U G I O
WILDER RANCH STATE PARK
Santa Cruz
Soquel
Capitola
NEW BRIGHTON STATE BEACH
CAPITOLA STATE BEACH
Soquel Cove
Opal Cliffs
U.S. COAST GUARD RESERVATION
NATURAL BRIDGES STATE BEACH



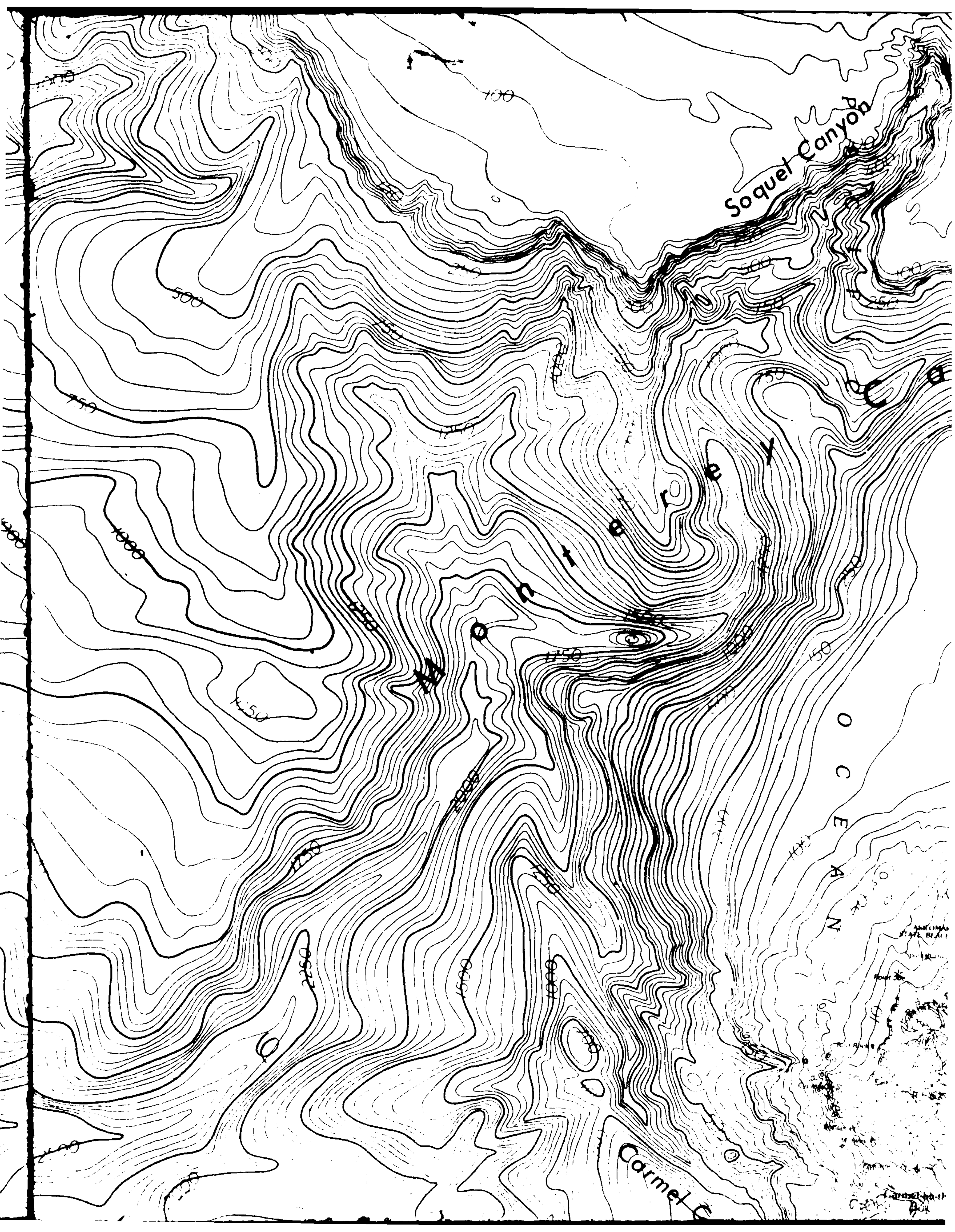
Almaden Reservoir
Manzanita Ridge
Morgan Hill
Chesbro Reservoir
Loma Prieta
SANTA CRUZ MOUNTAINS
SAN ANDREAS RIFT ZONE
Uvas Reservoir
San Martin
Eagle Ridge
SANTA CLARA CO
SANTA CRUZ CO
Mt. Madonna
Bodfish Creek
LAS ANIMAS
MT. MADONNA COUNTY PARK
Hecker Pass
Corralitos
LOS CORRALITOS
SALSIPUEDES
Santa Cruz Mountains
College Lake
Kelly Lake
Johnston Corner
La Selva Beach
MANRESA STATE BEACH
Watsonville
Pajaro
PAJARO VALLEY
Pajaro River
Mt Pajaro
Soda Lake
Chittenden
Aromas
VEGA DEL RIO DEL PAJARO
BOLSA DE SAN CAYETANO
LAS AROMITAS Y AGUA CALIENTE
MONTEREY CO



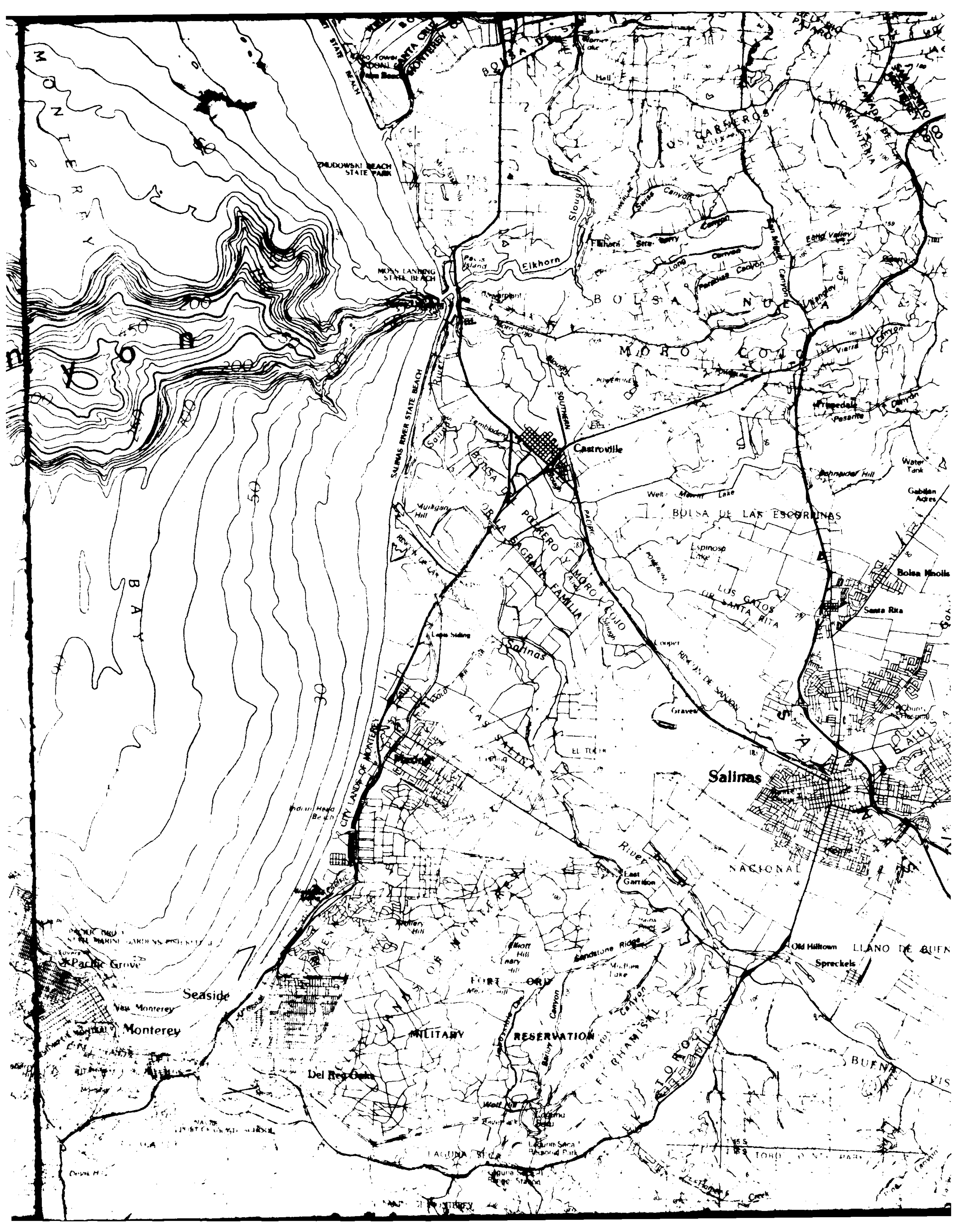
Kelly
Cabin
Canyon
Creek
Ridge
Sheep Ridge
Hunting
Hollow
Phegley
Ridge
Hagerman
Canyon
Elephant
Head
Ridge
Pigeon Point
SAN YSIDRO
AUSAYMAS Y SAN FELIPE
Gilroy
Old Gilroy
SAN YSIDRO
Santa
Clara
Llagas
Creek
Carnadero
Valley
River
San Felipe
Miller
Creek
Pajaro
Corporal
Sargent
Water Tank
Muertas
LOMERIAS MUERTAS
Water Tank
Hudner
Dunneville
Bolsa
BOLSA DE SAN FELIPE
HOLLISTER
SAN JOAQUIN
Airport
Santa
Ana
Cottage Corner
4



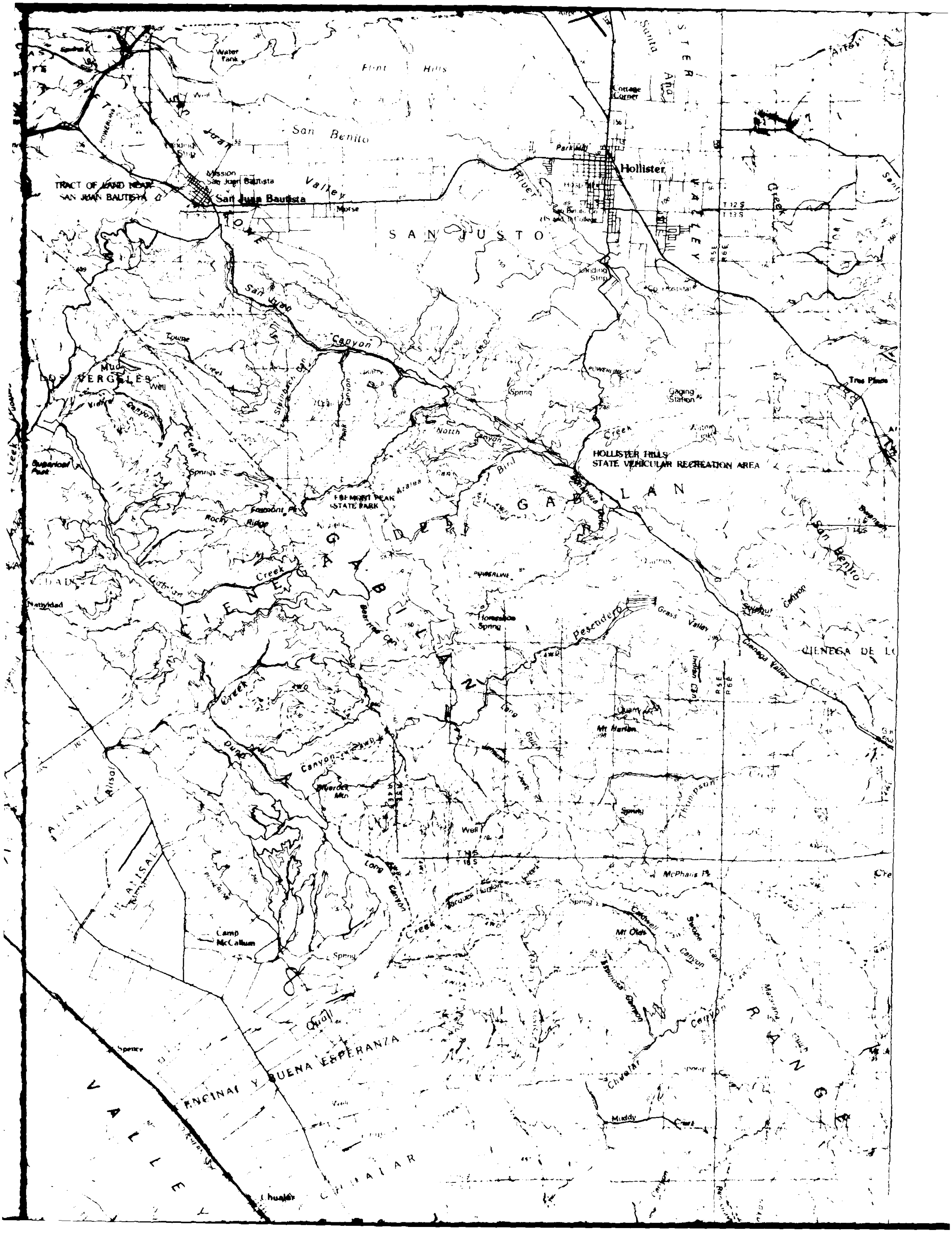
1750
1500
1750
2000
2750



Soquel Canyon
Monterey Ca
OCEAN
Carmel C
100
250
500
750
1000
1250
1500
1750
2000



MONTEREY
BAY
ZMUDOWSKI BEACH STATE PARK
MOSS LANDING STATE BEACH
SALINAS RIVER STATE BEACH
Elkhorn
Slough
BOLSA NUEVA
MORO COJO
Castroville
BOLSA DE LAS ESCORPINAS
Espinosa Lake
LOS GATOS OR SANTA RITA
Bolsa Knolls
Santa Rita
RINCON DE SANJON
Salinas
NACIONAL
CITY LANDS OF MONTEREY
Marina
Indian Head Beach
East Garrison
River
Pacific Grove
Seaside
New Monterey
Monterey
Del Rey Oaks
FORT ORD
MILITARY
RESERVATION
Sandstone Ridge
EL CHAMISAL
EL TORO
Old Hilltown
Spreckels
LLANO DE BUENA
BUENA VISTA
Laguna Seca Regional Park
Castroville
Swiss Canyon
Strawberry
Paradise Canyon
Prunedale
Schneider Hill
Gabilan Acres
Water Tank
Mulligan Hill
Lapis Siding
Creek



Hollister
San Juan Bautista
Mission San Juan Bautista
TRACT OF LAND NEAR SAN JUAN BAUTISTA
San Benito
Valley
SAN JUSTO
Front Hills
Cottage Corner
Water Tank
Landing Strip
Morse
LOS VERGELES
San Juan Canyon
HOLLISTER HILLS STATE VEHICULAR RECREATION AREA
FREMONT PEAK STATE PARK
Fremont Pk
Rocky Ridge
GABILAN
Gaging Station
Tres Pinos
Horseshoe Spring
Pescadero
Grass Valley
Cienega Valley
CIENEGA DE LOS
Mt Harlan
Thompson
Quarry
Well
Spring
McPhails Pk
Mt Olds
Camp McCallum
Long Canyon
ENCINAL Y BUENA ESPERANZA
CHUALAR
Chualar
Muddy Creek
Natividad
VALLEY
RANGE
POWERLINE
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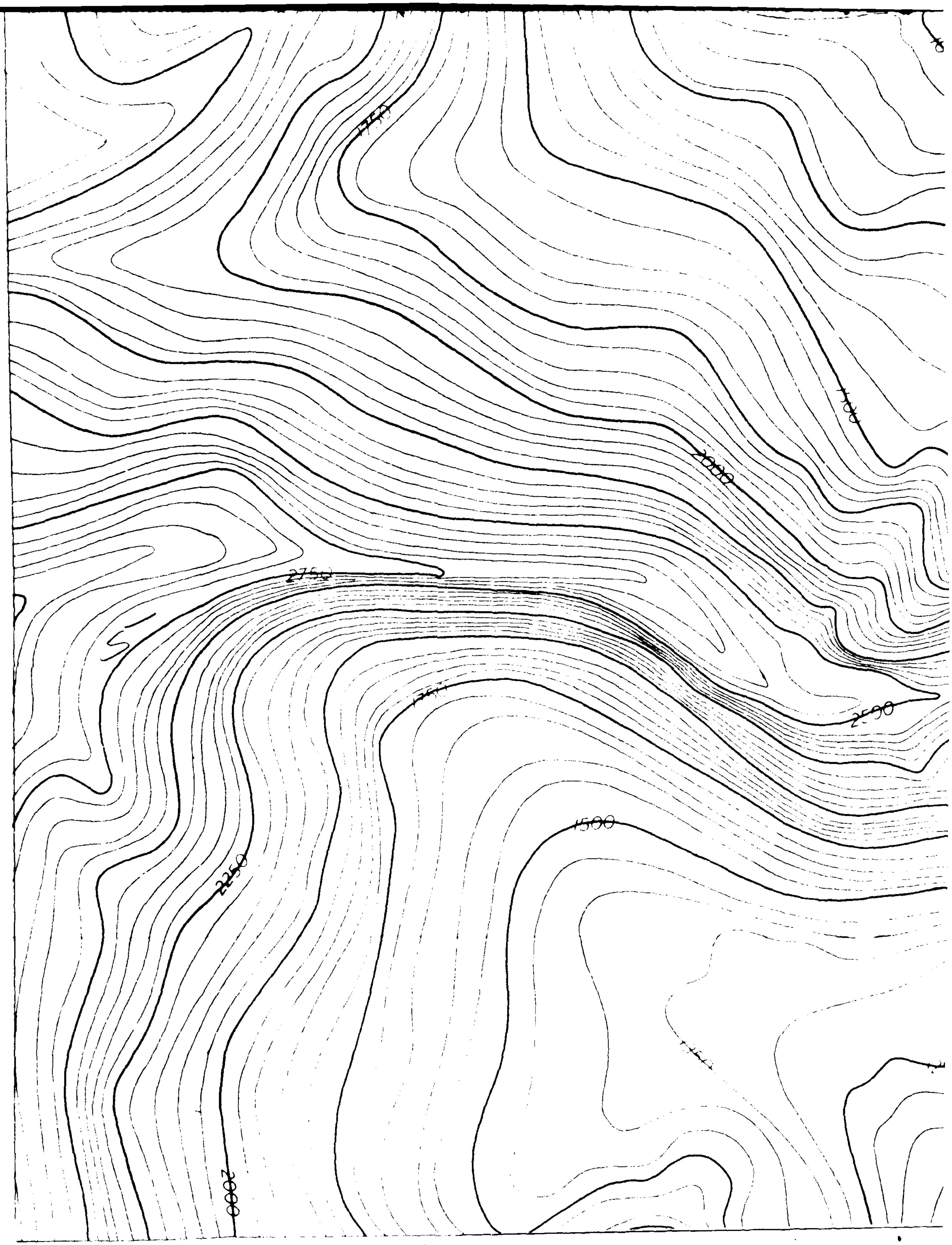
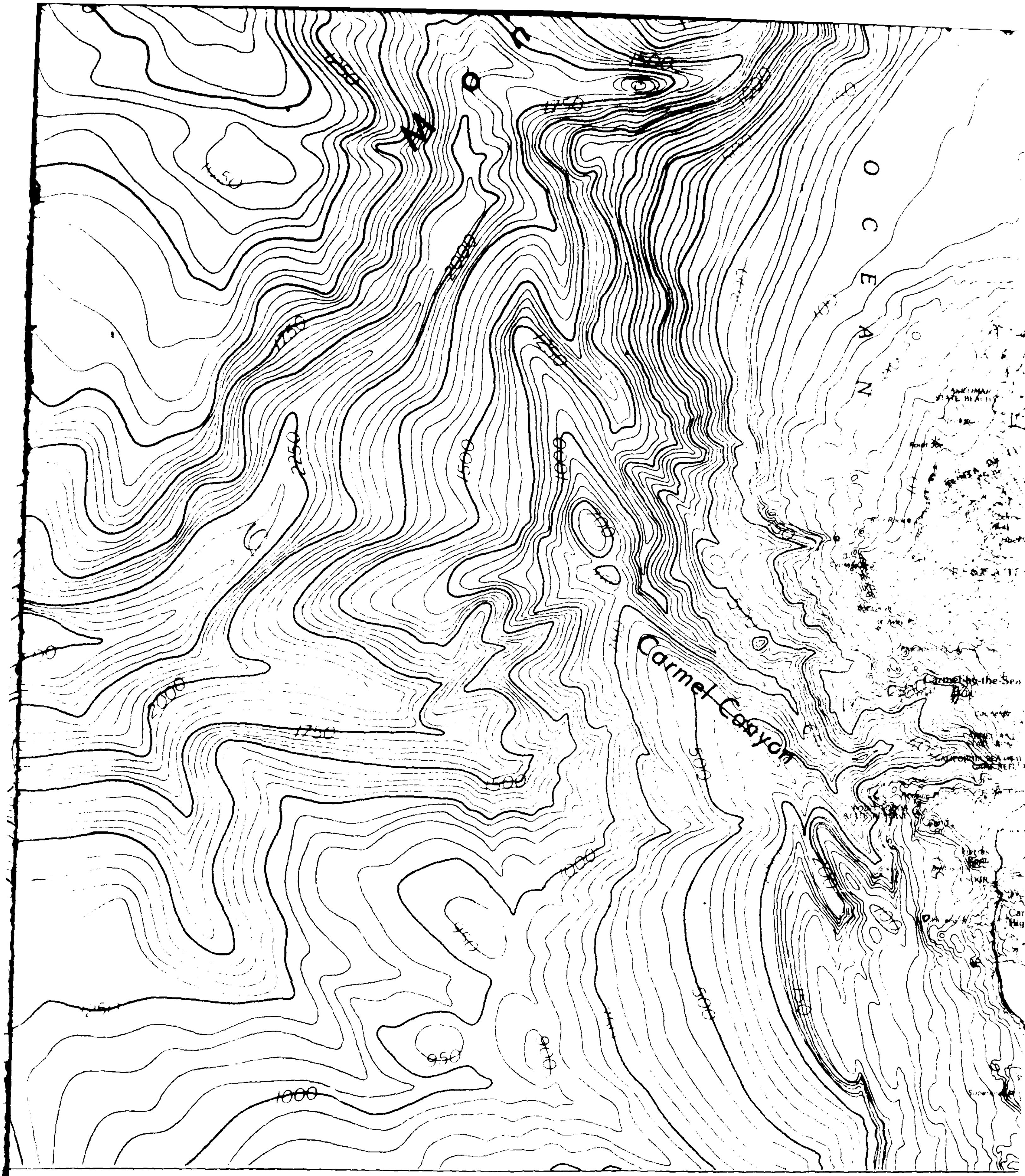
T 15 S
R 5 E
R 6 E



Basemap from U.S.G.S. topo sheets San Jose, Palo Alto, and Monterey, CA; bathymetry from Greene (1978) FOJ 26-30.


Carmel Canyon
O C E A N
Carmel-by-the-Sea
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terey, CA;

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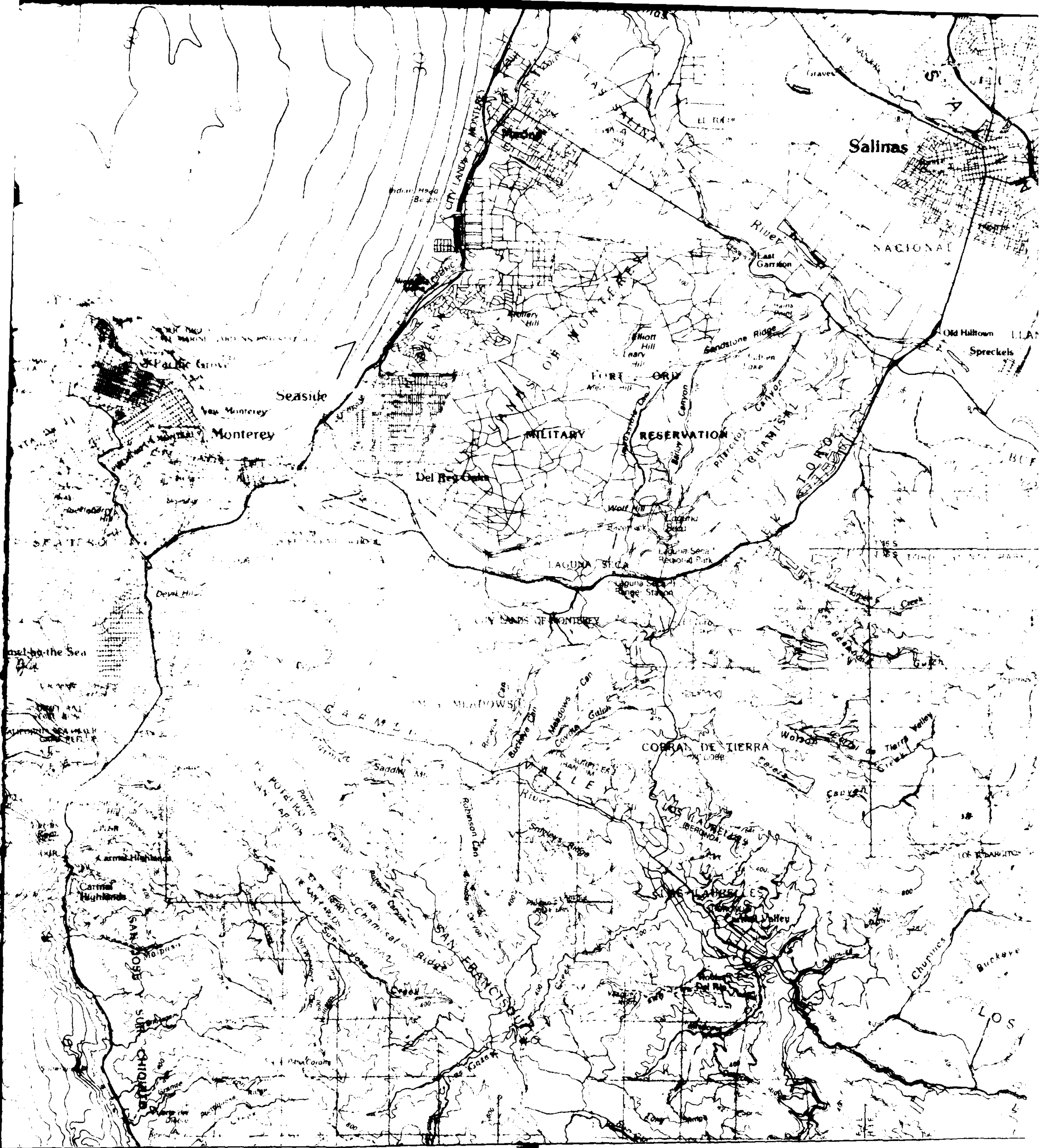

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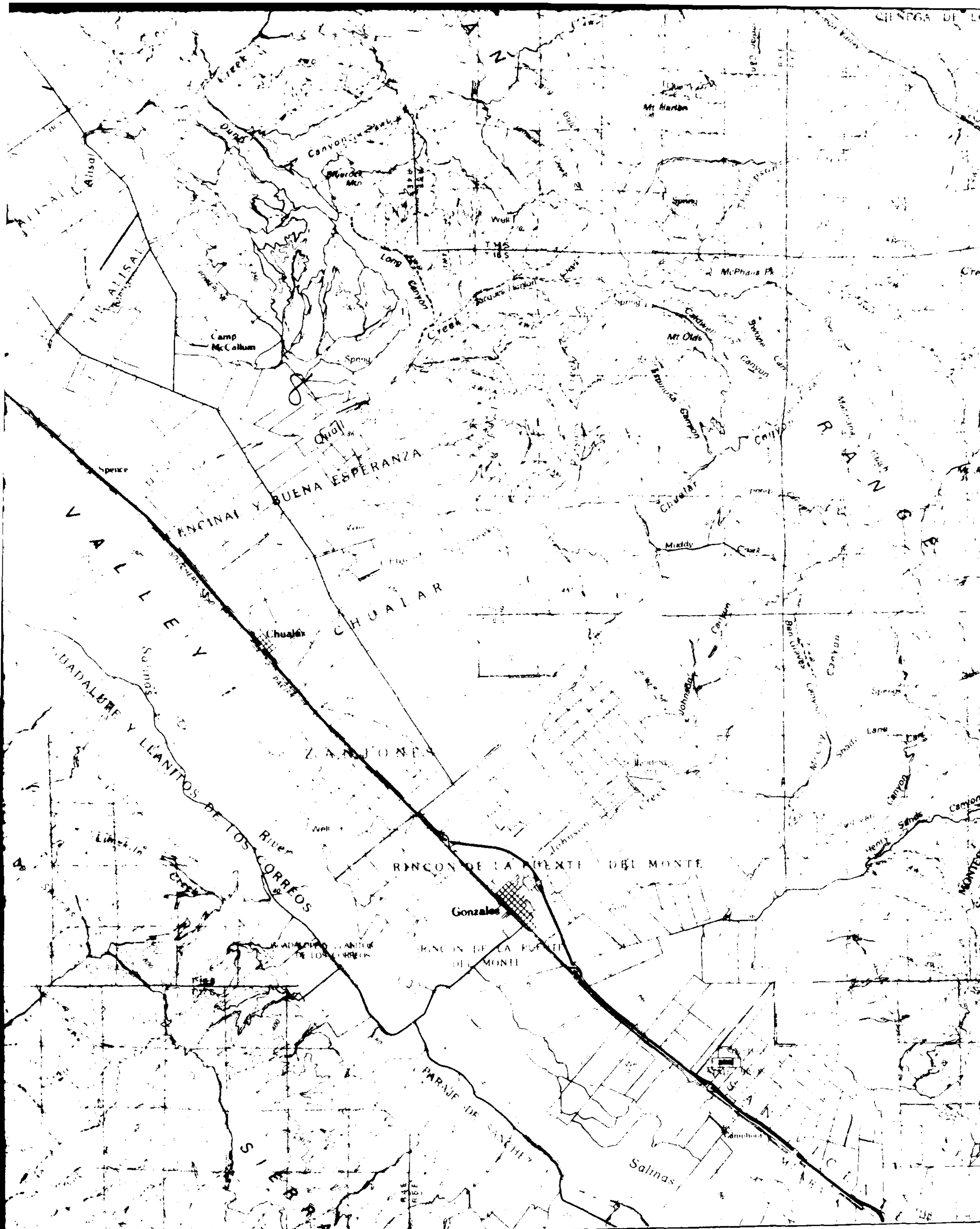
PLATE 1



COAST OF CALIFORNIA STORM AND TIDAL WAVE STUDY

POINT SANTA CRUZ TO POINT PINOS

TOPOGRAPHY AND BATHYMETRY

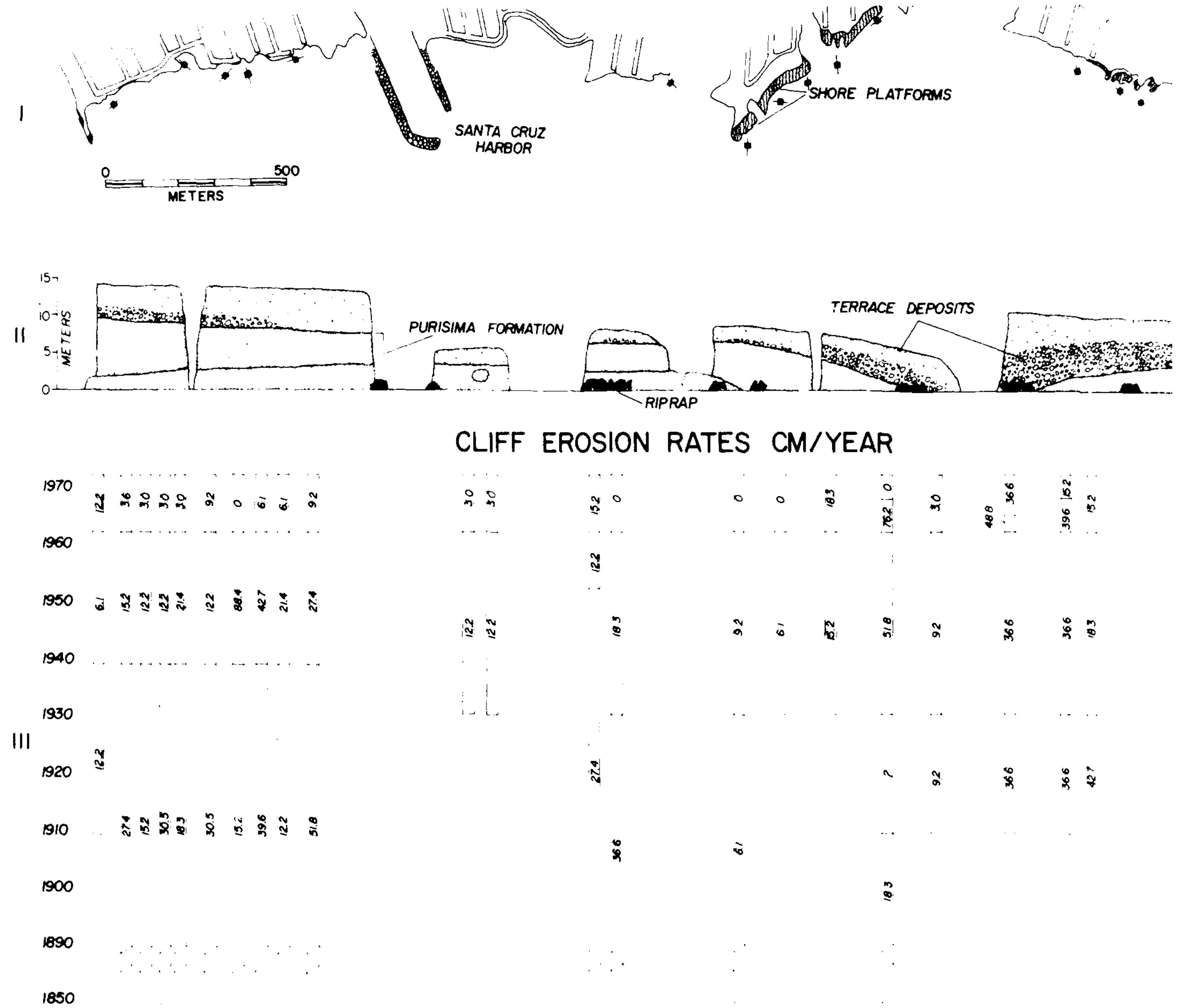


Figure 4-6 Plan view (I), cross section (II), and long term average erosion rates along northern Monterey Bay from San Lorenzo Point to Soquel Point (III). Note joint orientations on plan view and variations in elevation of terrace surface on cross section. Erosion rates are shown for specific intervals for which control exists. [from Griggs and Johnson, 1979]

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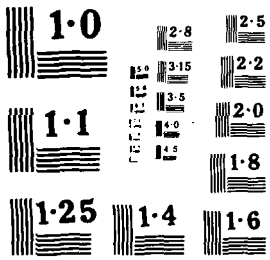
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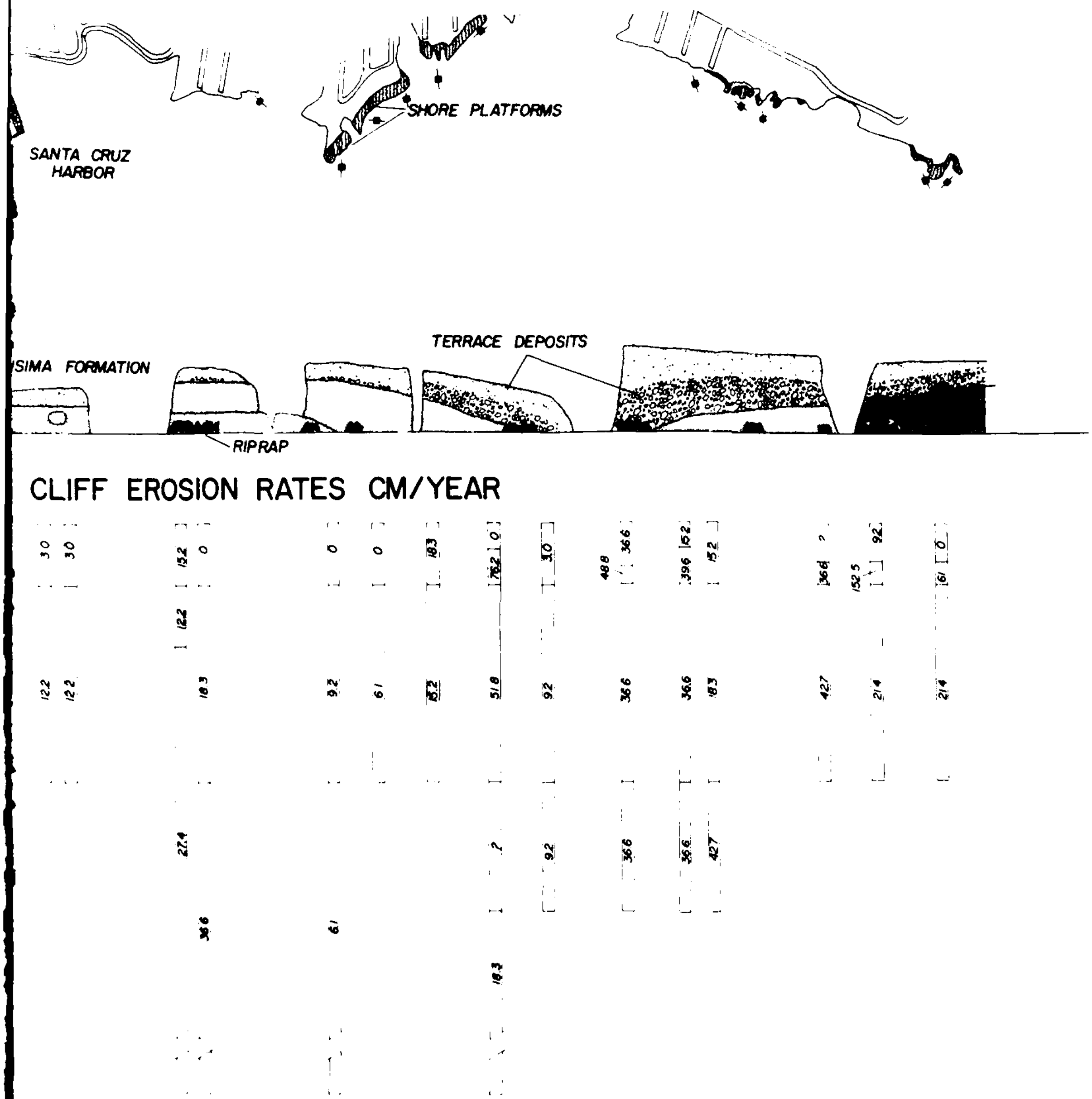


ction (II), and long term average erosion rates along north-
San Lorenzo Point to Soquel Point (III). Note joint orien-
d variations in elevation of terrace surface on cross section.
n for specific intervals for which control exists. [from Griggs

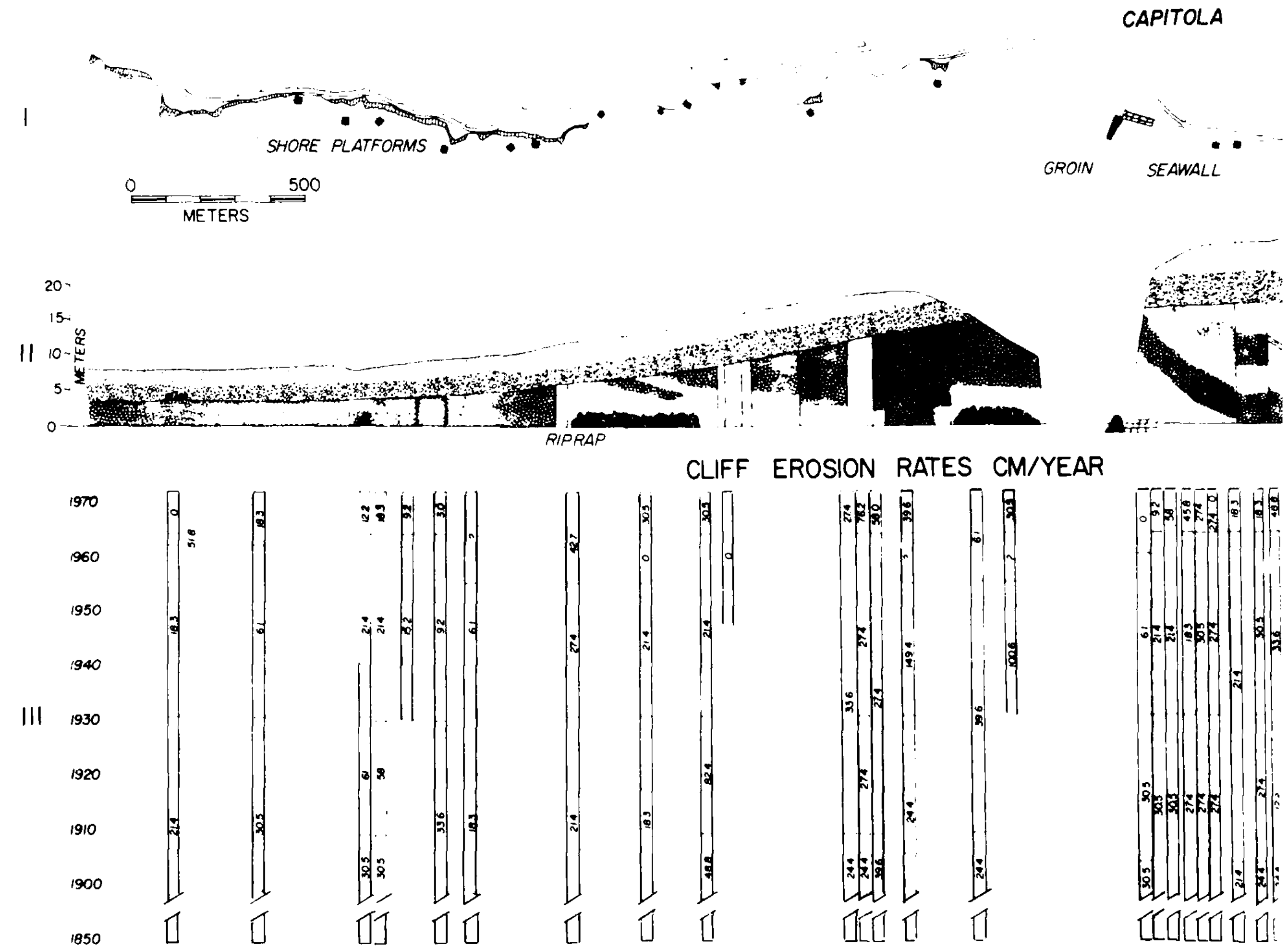
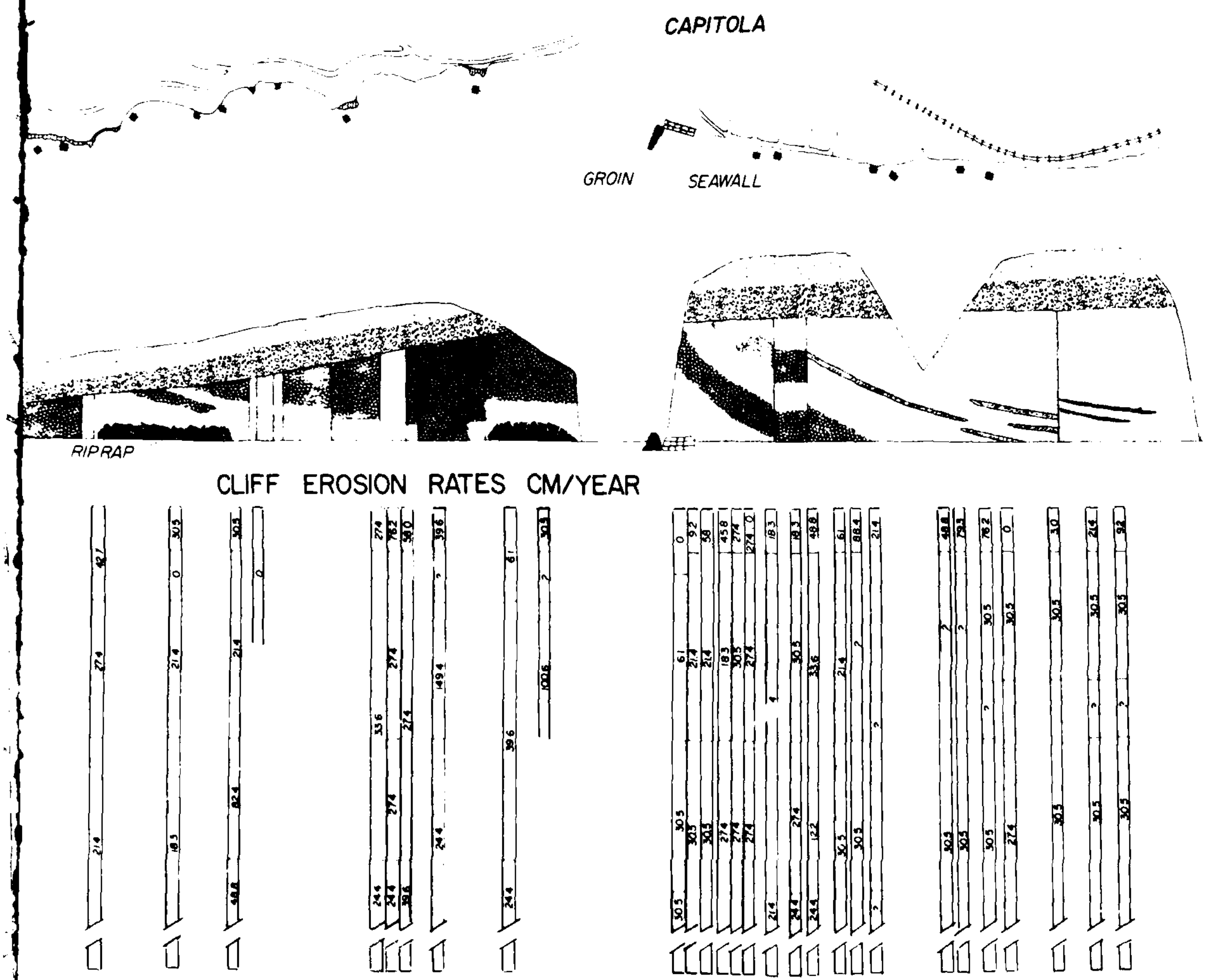


Figure 4-7. Plan view (I), geologic cross section (II), and long term average erosion rates along northern Monterey Bay from Soquel Point to Capitola (III). Note joint orientations on plan view, variations in elevation of terrace height, faulting in the bedrock, and shell horizons within the Purisima Formation. Erosion rates are shown for specific intervals for which control exists. [*from* Griggs and Johnson, 1979]



gic cross section (II), and long term average erosion rates along
Bay from Soquel Point to Capitola (III). Note joint orientations
ions in elevation of terrace height, faulting in the bedrock, and
in the Purisima Formation. Erosion rates are shown for specific
control exists. [*from* Griggs and Johnson, 1979]

1. Dams, reservoirs, and valley fills along Highway 1

2. Increased construction of artificial protection

3. The depletion of the "Año Nuevo point source", a 6-9 million m^3 reservoir of sand supplied to the littoral zone during the past 200 years when the channel between Año Nuevo Point and Island, located approximately 32 km north of Santa Cruz, was formed.

Therefore, Weber suggests, the sediment added from the Año Nuevo point source created a temporary buffer, decreasing cliff erosion during the past 100+ years; however, this point source is now depleted and the coastline has returned to its normal equilibrium condition of broad summer beaches and thin winter beaches accompanied by wave erosion and seacliff retreat.

4.14. From the south end of Rio Del Mar to approximately La Selva Beach, terrestrial erosion has created extensive gullies that historically have very high rates of erosion. Figure 4-8 illustrates the approximate change of cliff-top location between 1940 and 1976 just north of La Selva Beach. The cliffs in this area, composed of the Quaternary Aromas Sandstone, are extremely gullied and have eroded as much as 16 m over 36 years, giving a maximum erosion rate of 44.4 cm/yr. Gullying, therefore, can result in significant cliff recession and, especially in the Aromas Sandstone, can produce a significant amount of littoral-size sediment.

SEDIMENT YIELDS

4.15. Dittmer (1972) estimated that the total sediment load contributed by north bay cliff erosion during an average year is approximately 75,000 m^3. This estimate is based on the U.S. Army Corps of Engineers (1969) estimate of 30.5 cm/yr of erosion and only considers the 8+ km of coastline between Santa Cruz and Seacliff State Beach. Dittmer's estimate does not include the 6+ km of coastline between Seacliff State Beach and La Selva Beach. His estimate also assumes that total sediment load equals the littoral sediment load, which, as the grain-size data indicated, is not the case. These two problems, however, tend to counter-balance each other: the sediment yield estimate would be enlarged if one considered the entire length of cliffed coastline, and the estimate would be significantly reduced using only the littoral-size sediment. Therefore, for an average year, approximately 75,000 m^3 may be a fairly good approximation. Dittmer's estimate, however, does not take into account the episodic nature of cliff erosion, whereby rapid erosion occurs during large storms and/or major block failure. Therefore, long-term average erosion rates must be used with caution.

South Bay

BLUFF DISTRIBUTION

4.16. Bluffs in semi-consolidated to unconsolidated relict dunes of Flandrian age (3000-5000 yrs. b.p.) make-up the majority of the shoreline of Monterey Bay from La Selva Beach southward to Del Monte Beach. The dunes are patchy between La Selva and the Salinas River and then a great dune mass of both Flandrian and pre-Flandrian age, covering 105 square km, extends south from the Salinas River to Del Monte. Cooper (1967) called this great dune mass the Monterey dune complex.

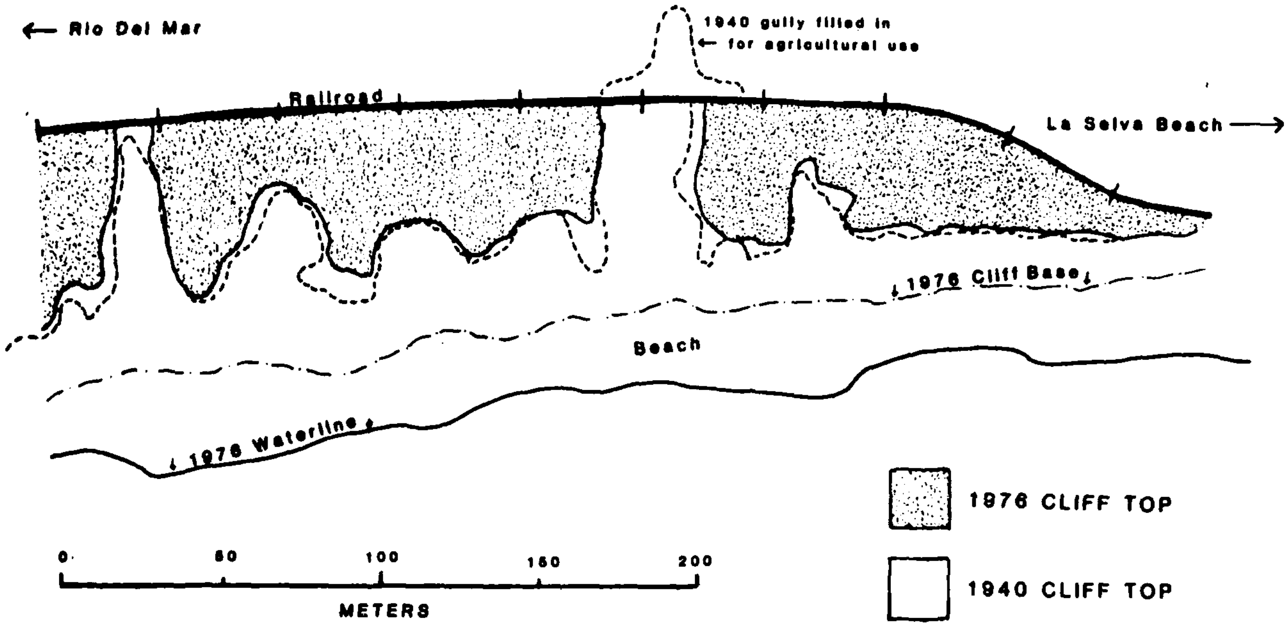


Figure 4-8. Approximate change of cliff top location between 1940 and 1976 (from aerial photographs, not corrected or tied into vertical datum)

4.17. The Flandrian dunes from La Selva Beach to the Pajaro River overlie non-eolian sediments of an uplifted marine terrace. Cooper (1967) noted one location where the dune sand has been almost swept clear, exposing the marine terrace in the center of this dune complex (fig. 4-1). Cooper (1967) described the area between the Pajaro and Salinas rivers as four bodies of stabilized dune sand with little relief, no distinct form, and some shallow undrained depressions. The dune belt, which runs along the shoreline between the Pajaro and Salinas rivers, never fully developed or has been destroyed by the shifting of these two rivers. Figure 4-9 shows that the southern bay shoreline, from the Salinas River mouth to Del Monte, is fringed by Flandrian dunes. Cooper (1967) studied this area in detail and noted the following geomorphic characteristics: these relict dunes form a belt of parabolic structures 200-700 m wide and usually 2-4 times as long, they are backed by almost 100 km^2 of pre-Flandrian dunes that are possibly underlain by marine terrace deposits, the long axis of the parabolic dunes runs perpendicular to the shoreline and is cleanly truncated on the seaward end, and the landward end rests on the pre-Flandrian dune surface. Most of the dunes from La Selva to Del Monte are relict or inactive; however, there are patches of active dunes near the Salinas River mouth and along the southern bay shoreline. The inactive, stabilized dunes are eroding on the seaward edge and are, therefore, an important sediment source.

SEDIMENT CHARACTERISTICS

4.18. Comparing grain texture, overall lithologic composition, and heavy-mineral composition from the dune sediments in the bluffs along the shoreline with those sands found on the beaches helps to show the significance of the relict dunes as a potential source of littoral sediment.

Sediment Texture

4.19. Combellick (1976) compared the average grain size and sorting of the Flandrian and pre-Flandrian dunes to that of the southern bay beach sands in both summer (June) and winter (February) conditions. Table 4-2, which summarizes his results, shows that the dune sands (average grain size = 0.4 mm) are finer than the southern beach sands (0.6 mm); however, the dunes do contain an average of 76 percent medium-to-coarse sand (>0.25 mm). Approximately 90 percent of the southern beach material is medium-to-coarse sand, therefore, the dunes are a potential source of significant amounts of littoral sediment.

4.20. Combellick (1976) also examined grain microtexture using a scanning electron microscope. Quartz grains from the pre-Flandrian dunes often showed evidence of silica precipitation, quite common on the surface of quartz grains in dune sand. He found that the surfaces of some quartz grains on the southern beaches had polished remnants of these precipitation layers, verifying the potential for contribution of medium-to-coarse sand to the southern beaches by dune erosion.

Mineralogy

4.21. **Overall Lithology:** Grain-size data indicated that the relict dunes that fringe the southern coast are a potential source of beach sediment. Table 4-3, from Combellick (1976), lists the overall lithologic composition of the 0.35 to 0.50 mm fraction from the Flandrian dunes, pre-Flandrian dunes, and southern beaches. Lithologic compositions from both dune samples are almost identical to that on the southern beaches, therefore, reaffirming that the dunes are a potential source of sediment for the beaches.

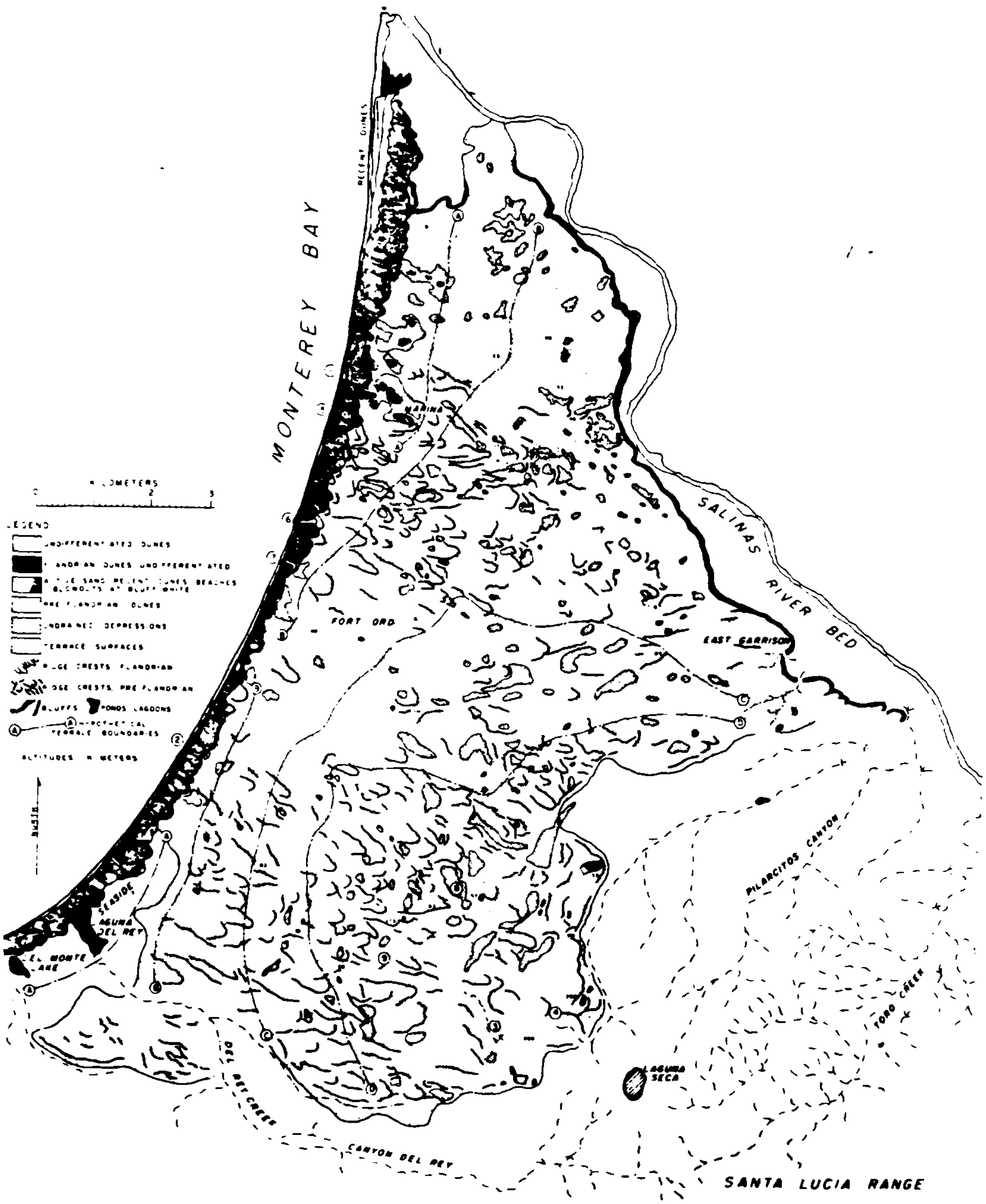


Figure 4-9. Distribution of coastal dunes in southern Monterey Bay [*from* Cooper, 1967]

Sample Location	Mean Grain Size (mm)	Mean Grain Size (phi)	Sorting Coefficient	Avg. % Greater Than	
				0.25 mm	0.50 mm
Southern Beaches (February)	0.8	0.6	0.7	89	61
Southern Beaches (June)	0.8	0.6	0.6	92	59
Flandrian dunes	0.5	0.4	0.5	78	22
Pre-Flandrian dunes	1.6	0.4	0.6	74	22

Table 4-2. Mean grain size and sorting of dune and beach samples in southern Monterey Bay [*from* Combellick, 1976 and Yancey, 1968]

4.22. **Heavy Minerals:** Yancey (1968) sampled the dune sand just north and just south of the Salinas River and analyzed the heavy-mineral fraction. He found that the heavy-mineral fraction was 92-95 percent hornblende, augite, and garnet. This almost matches with Sayles (1966) heavy-mineral analysis of the southern beach sands, which he calls the hornblende-garnet province.

BLUFF EROSION

4.23. The same processes of marine and terrestrial erosion, which were described in the north bay cliff-erosion section, also act on the bluffs of the southern bay. Just as in the northern part of the bay, marine erosion is the dominant process, although terrestrial processes do create extensive gullies in some locations. Cooper (1967) explained that the Flandrian dune belt must have narrowed considerably since its formation 3-5000 years ago because the maximum height of the dunes implies a much broader belt. Therefore, the dunes continually add material to the shoreline. He states that, under wave attack, the unconsolidated Flandrian sands slide to the beach and the more coherent, underlying pre-Flandrian sands are often undermined and break off in large blocks.

Historical Changes

4.24. Griggs (pers. comm., 1985), who has studied the Monterey Bay coastline extensively, stated that the inner coastline of Monterey Bay, from New Brighton Beach at the north to Del Monte Beach at the south has been, in the past, an equilibrium coastline with sediment input equaling sediment output. Wide, sandy beaches and the extensive sand dunes indicate that sand supply probably exceeded sand loss in the past. However, Grigg's field observations and his analysis of the historical record (dating back 70 years) indicate that the coastline of southern Monterey Bay is now eroding. He found that average annual erosion rates from Marina to Sand City were 0.76 t over 3.0 m/yr and decreased to approximately 0.5 m/yr from Sand City to the Monterey Municipal Wharf.

4.25. Bluff erosion is most extreme in the vicinity of Ft. Ord. Arnal and others (1973) reported that erosion in this area has accelerated, increasing from approximately 0.5 m/yr in the 1920s'

Constituents	Flandrian dunes	Pre-Flandrian dunes	Southern beaches
MONOCRYSTALLINE GRAINS			
Non-undulatory quartz	2	2	2
Undulatory quartz	44	42	41
K-feldspar	14	18	17
Plagioclase	14	13	12
Accessory minerals	tr	1	1
Unidentified minerals	1	2	2
ROCK FRAGMENTS			
Granite	7	7	9
Plutonic quartz	6	7	7
Metamorphic quartz	tr	tr	tr
Orthoquartzite	1	1	1
Arkose, subarkose	tr	1	1
Graywacke	1	1	tr
Siltstone	2	1	1
Shale	1	tr	tr
Chert	2	2	2
Felsite	1	tr	tr
Unidentified	4	3	3
Shell material	-	-	tr
Avg. % represented by 0.35-0.50 mm fraction	26	21	14

Table 4-3. Average percentage lithologic composition of the 0.35 to 0.50 mm size fraction of dune and beach samples in southern Monterey Bay [*from* Combellick and Osborne, 1977]

to almost 1.0 m/yr in the 1950s' to over 1.5 m/yr in the 1960s'. Recently, the U. S. Army Corps of Engineers (1983) reported a retreat rate of 2.0 m/yr at Ft. Ord. Griggs (pers. comm., 1985) found erosion rates to be 2.6 m/yr in this area at present. The trend of increased erosion rates in the southern part of the bay is well substantiated by these three separate reports.

4.26. Bluff erosion is most extreme after winter storms have removed the protective beach. Erosion, therefore, tends to occur episodically, just as severe storms that strike the coast occur episodically. Dingler and others (1985) profiled the Ft. Ord Beach from the top of the bluff to wading depths in the swash zone 12 times between February 3, 1983 and January 17, 1985. Figure 4-10 illustrates that the bluffs eroded almost 10 m over the 20 day period from February 4 to February 24, 1983. Bluff erosion then ceased for almost two years from February 24, 1983 to January 17, 1985. Average annual erosion rates, therefore, must be used with caution, considering the episodic nature of bluff erosion.

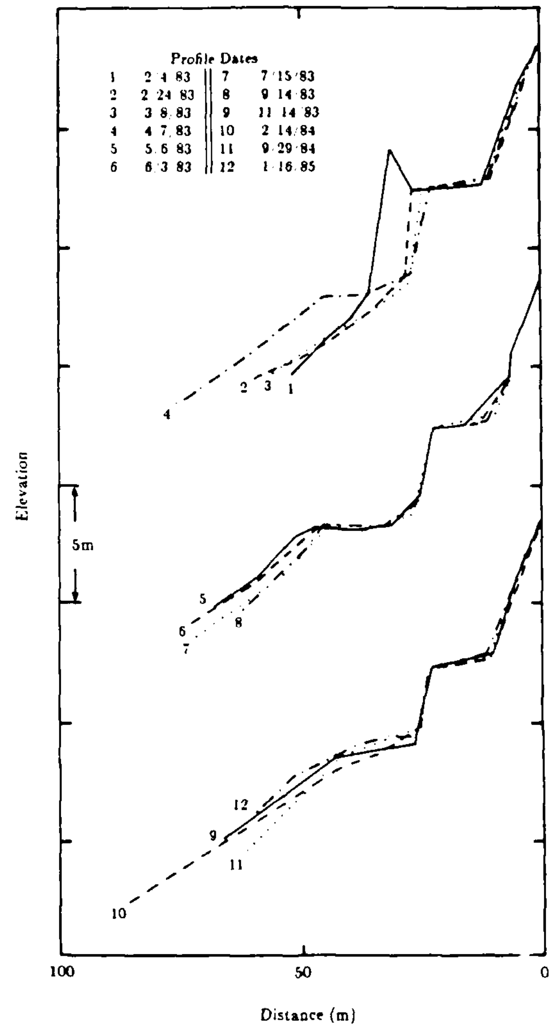


Figure 4-10. Ft. Ord Beach profiles, February 3, 1983 - January 17, 1985 [*from* Dingler and others, 1985]

SEDIMENT YIELDS

4.27. Dorman (1968) estimated the average annual sediment yield of material coarser than .0625 mm from the south bay dunes to be 176,000 m^3/yr between 1945 and 1968. His estimate is based on an average bluff erosion rate of 1.2 m/yr over 14 km of coastline with an average bluff height of 11.5 m. Arnal and others (1973) estimated the average annual sediment yield (total load) from the same south bay area to be 229,000 m^3/yr between 1944 and 1961. Using Combellick's (1976) estimate that the dune sands average 76 percent medium-to-coarse sand, Arnal and others' estimate of the total load is reduced to 174,000 m^3/yr; therefore, almost equal to Dorman's estimate.

4.28. Arnal and others (1973), however, feel that the sediment yield from bluff erosion is increasing as the erosion rates accelerate. They estimated that, between 1944-1961 and 1961-1967, erosion rates increased from 1.0 to 1.5 m/yr and sediment yields (total load) increased from 229,000 to 380,000 m^3/yr. This represents and increase from 174,000 to 290,000 m^3/yr of littoral-size sediment. Assuming that the current erosion rate averages 2.0 m/yr, then the current total sediment yield from bluff erosion is roughly 450,000 m^3/yr or 340,000 m^3/yr of littoral-size sediment.

Summary

4.29. Approximately 15 km of seacliffs extend from Point Santa Cruz to La Selva Beach; and 23 km of bluffs, on the seaward edge of the central and southern bay Flandrian dune belt, extend from La Selva Beach to Del Monte Beach. The sediments of the north bay beach sands and the coastal cliffs are strikingly similar, indicating that the cliffs are a significant source of littoral sediment. Two of the three rock types found in the cliffs (Purisima Formation and the Aromas Sandstone) and the overlying Quaternary terrace deposits contain an appreciable amount of littoral-size sediment (52-74% in many units). Cliff erosion in northern Monterey Bay is predominantly a marine process, although extensive gullying (up to 44.4 cm/yr) occurs north of La Selva Beach. Historical rates of cliff erosion indicate the following:

1. Erosion has been occurring from Point Santa Cruz to Capitola since at least 1850

2. Erosion in the New Brighton Beach area is a relatively new phenomenon, but was quite common up to about 100 years ago, which may be, in part, related to the formation of Año Nuevo Island to the north.

The average annual yield of littoral-size sediments from the cliffs is approximately 75,000 m^3/yr, but this figure must be used with caution because the estimate is rough and does not consider the episodic nature of cliff erosion.

4.30. The sediments of the south bay beaches and the Flandrian and pre-Flandrian dunes are also strikingly similar, suggesting that the dune bluffs are a significant source of littoral sediment. The inactive dunes contain an average of 76 percent medium-to-coarse sand. Bluff erosion along the southern bay coastline is predominantly a marine process. Historical rates of erosion indicate that the rate of bluff recession is increasing and, at present, may be as high as 2.6 m/yr in some locations. The average annual yield of littoral-size sediment from the bluffs is approximately 340,000 m^3/yr, assuming that average annual erosion rates have increased to approximately 2.0 m/yr.

4.31. Average annual rates of erosion and average sediment yields from the cliffs and bluffs along the entire coastline of Monterey Bay are fairly well documented. Erosion rates are much higher in the unconsolidated bluffs along the southern bay coastline. Erosion rates, in both the northern cliffs and in the southern bluffs, appear to have increased in the recent, historical past. The factors causing these increasing erosion rates are most likely related to the following:

1. Reduced sediment input from the drainage basins

2. Extensive sand mining on the beaches in the southern bay

3. Increased amount of coastal construction

4. Depletion of the Año Nuevo point source

5. More severe storms in the past decade

All these factors are significant to some degree, however, whether one factor significantly outweighs the others is not clear.

5. NEOTECTONICS OF MONTEREY BAY

5.1. This section reviews the tectonic, sedimentologic, and glacio-eustatic sea-level fluctuations that have occurred in the Monterey Bay area. An overview of the Tertiary through Pleistocene events that led to the present onland and offshore morphology elucidate the active nature of the area. The geologic history from the Cretaceous through Pleistocene time periods will be summarized with an emphasis on events that led to the area's present configuration.

5.2. The present geomorphology of the Monterey Bay area is very complex because variable amounts of interplate movement have produced localized tectonic uplift and subsidence and associated faulting. The area lies on a Cretaceous granitic mass that has been displaced to the north along the San Andreas Fault Zone; the fault marks the contact between the North American and the Pacific plates. The character of interplate movement is responsible for episodes of emergence and subsidence of large blocks within the main granitic mass. These blocks are separated by numerous northwest-southeast and east-west trending faults. Tertiary to Holocene stratigraphic sequences indicate deposition in various environments including deep marine basins, continental shelves, esturaries, and coastal sand dunes.

TECTONICS

5.3. Monterey Bay lies on a major structural unit known as the Salinian Block (Page, 1970). This elongate block consists of granitic rocks of Cretaceous age and is bounded on the east and west by a heterogenous aggregation of Jurassic and Cretaceous eugeosynclinal rocks of the Franciscan assemblage. The granites that comprise the Salinian block are of two types; in the north the Ben Lomond Mass is a quartz monzonite without phenocrysts, and in the south the Monterey Mass is primarily a porphyritic granodiorite with large phenocrysts of potassium feldspar. The Salinian Block is bounded on the east by the San Andreas Fault and on the west by the Palo Colorado-San Gregorio Fault Zone (fig. 5-1). The block extends from the Transverse Ranges to Cape Mendocino, a distance of approximately 800 km (Page, 1970; Silver and others, 1971); the San Andreas Fault marks the contact of the North American and Pacific plates. Hill and Dibblee (1953), King (1959),and Page (1970) are among those who feel that the Salinian Block is a mass of Sierrian granitic basement that moved north during Tertiary time. Ross (1978), however feels that, because petrological analysis cannot determine the origin of the Salinian Block, it is a granitic "orphan" (Greene and Clark, 1979).

5.4. Investigators have divided the Monterey Bay area into smaller, uplifted blocks and basins that are separated by southeast-northwest trending faults (fig. 5-2; Lawson, 1914; Clark and Rietman, 1973, Clark 1930, Starke and Howard, 1968; Martin and Emery, 1967; Greene and others 1973; Ross and Brabb, 1972). The offshore area has been divided into a series of basins and basement ridges (fig. 5-3) (Curray, 1965, 1966; Hoskins and Griffiths, 1971; Silver and others, 1971), and its subsurface stratigraphy described in detail by Greene (1977). The onset of slivering of the Salinian Block first occurred during Neogene time, (Johnson and Normark, 1974; Howell, 1976; and Greene and Clark, 1979), or in the late Cretaceous (Howell, 1975; and Clarke, Howell, and Nielsen, 1975).

5.5. Beginning in the Neogene and continuing to the present, tectonic uplift and subsidence has occurred, creating movement called wrench fault tectonics by Greene (1977). Wrench fault tectonics results from episodes of emergence and subsidence of large blocks within the main Salinian Block. These blocks are separated by numerous northwest-to-southwest trending faults

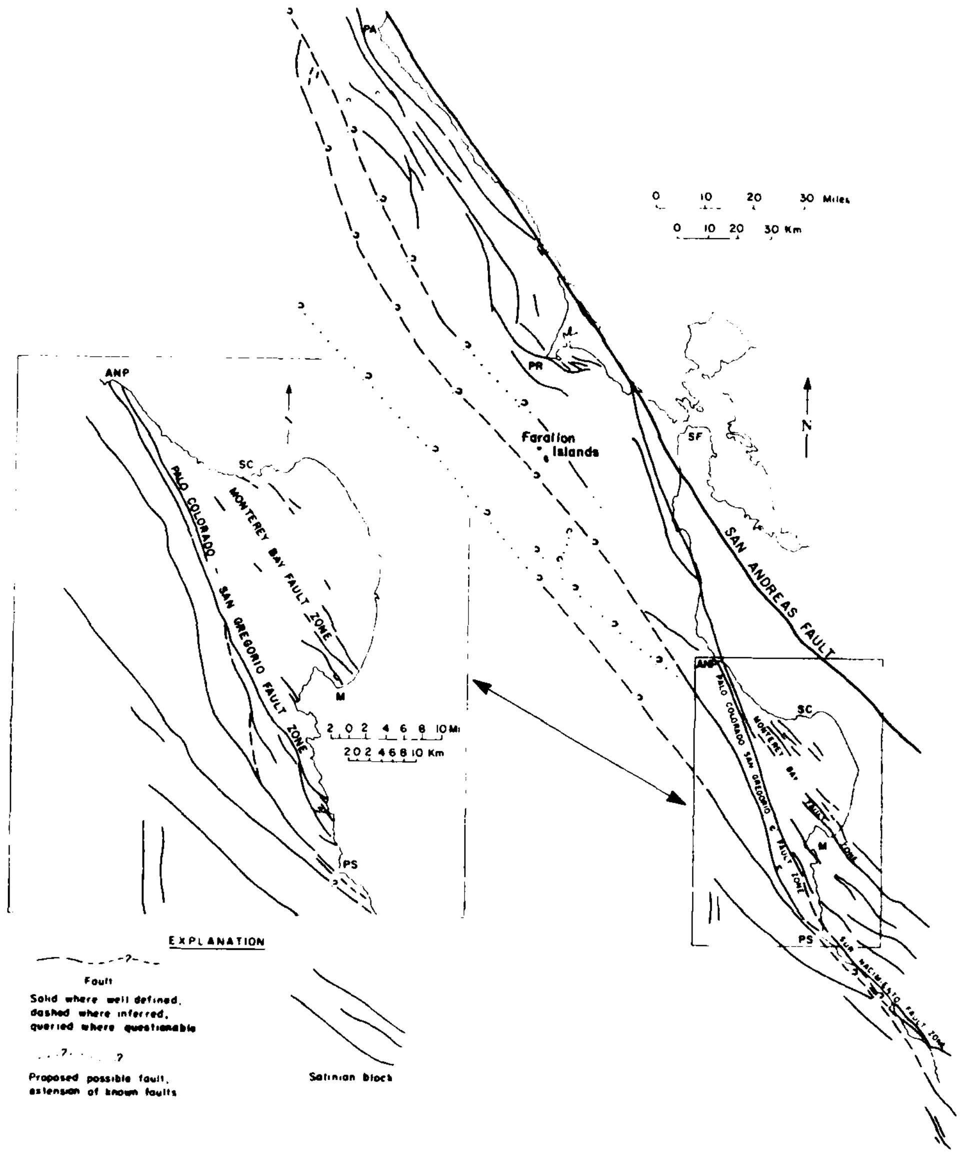


Figure 5-1. **Map showing proposed boundary of the northern half of the Salinian block.** [*taken from* Greene and Clark, 1979].

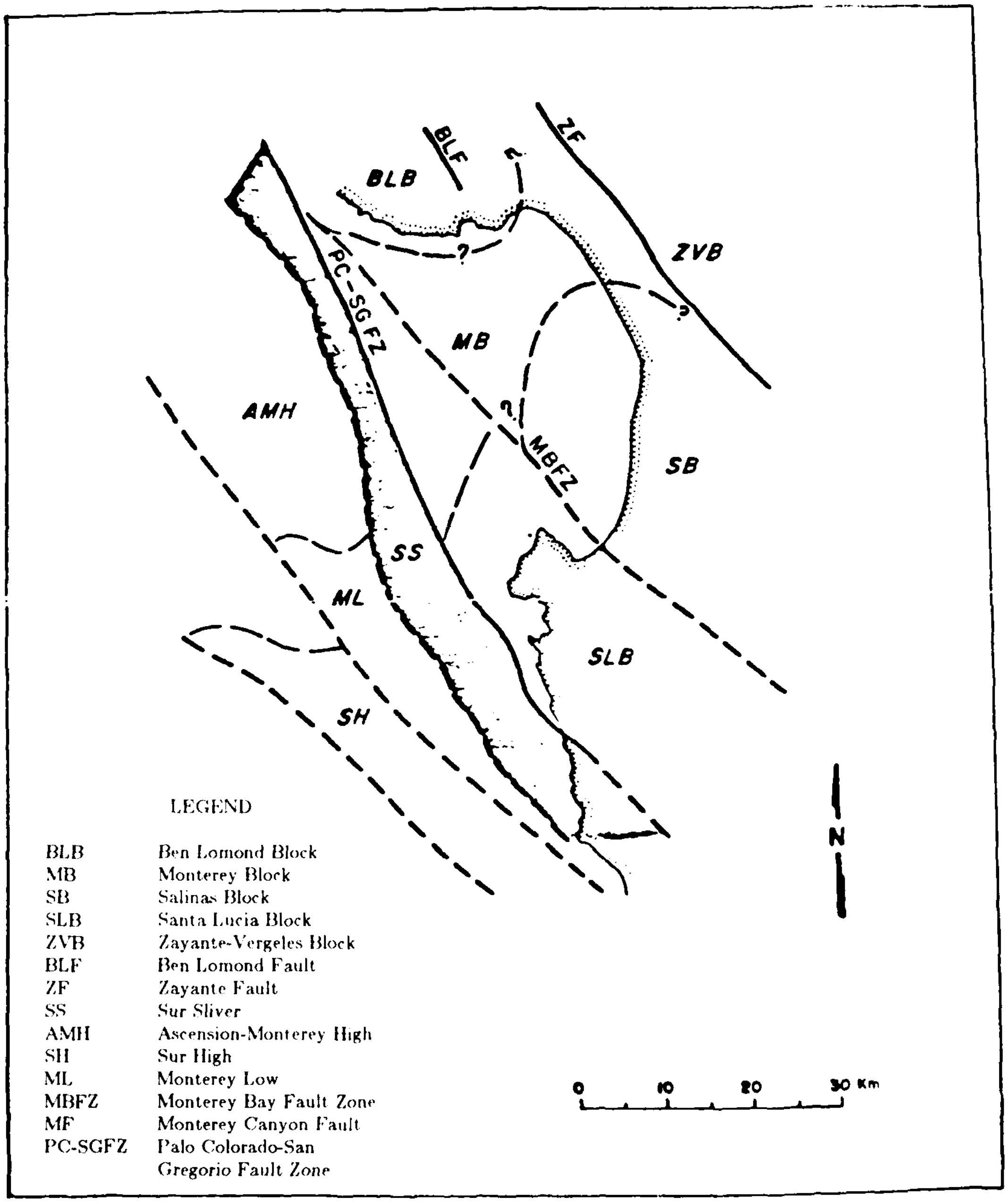


Figure 5-2. Orographic blocks of the Monterey Bay region based on offshore geophysical data. [*from* Greene, 1977]

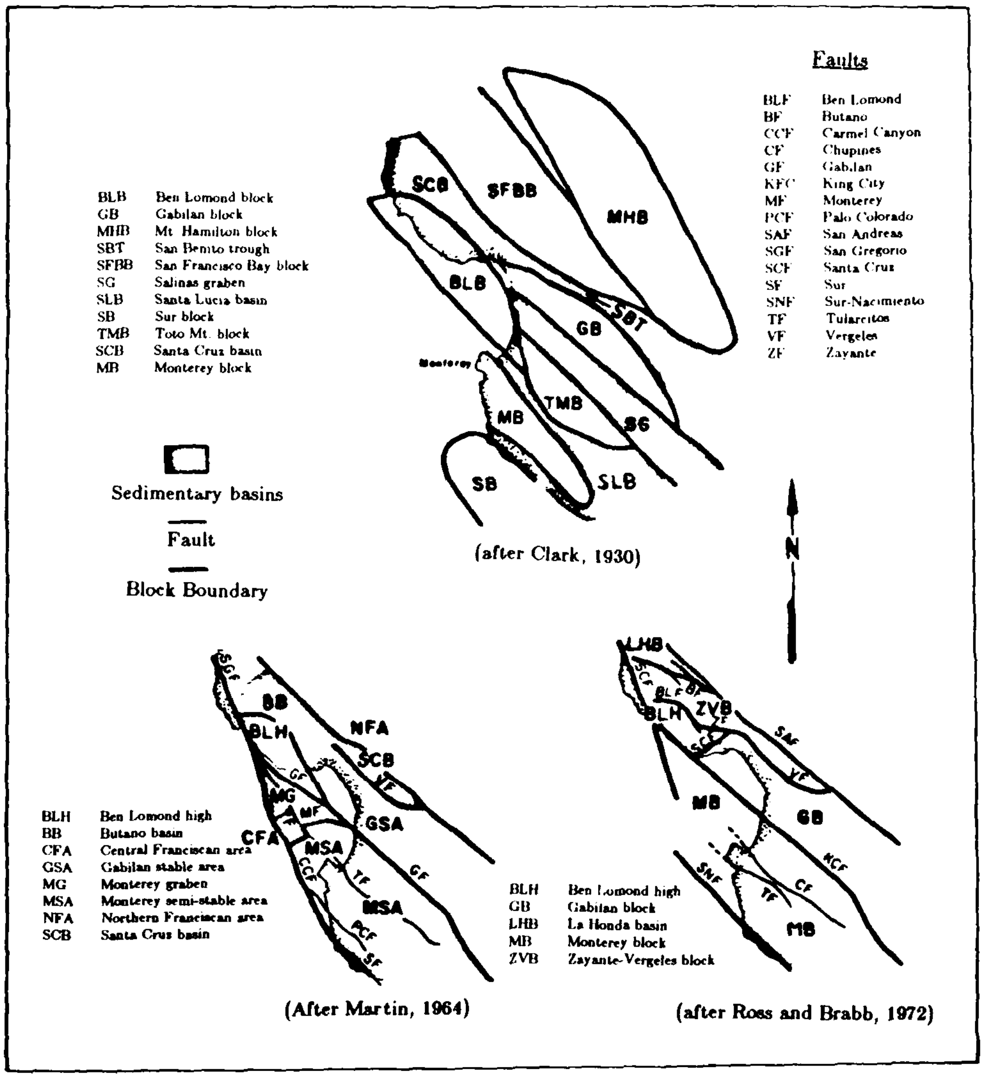


Figure 5-3. Historical development of orographic blocks. [*from* Greene, 1977]

(fig. 5-2).

Since the Oligocene, these fault-bounded blocks have shifted and moved as the Salinian block itself moved in a northwest direction from its initial position adjacent to the Transverse Ranges.

OFFSHORE

5.6. Submarine physiography is dominated by the Monterey Submarine Canyon. The canyon, which extends over 90 km in a east-west orientation, dissects the broad flat continental shelf and heads less than .5 km west of Elkhorn Slough. Greene (1977) suggests Oligocene time for down-cutting of Monterey, Carmel, Soquel, and Ascension Canyons. Monterey Canyon joins one of its three tributaries, Carmel Submarine Canyon, approximately 10 km northwest of Point Pinos, where its greatest relief (1,830 m) is found. The canyon is joined by its two other tributaries, Asension and Soquel Canyons, on the northern half of the bay (Greene, 1973).

5.7. Greene (1977) divided the offshore area into four orographic blocks; the Ben Lomond, Monterey, Salinas and Santa Lucia. The Ben Lomond Block plunges abruptly to the southwest with strata of the Monterey Block lapping onto and wedging out on the Ben Lomond Block. The Monterey Block extends from the onshore Zayante Fault westward to the Palo Colorado-San Gregorio Fault Zone. Monterey Canyon separates the Monterey Block from the Salinas Block and the Monterey Block from the Santa Lucia Block. The Santa Lucia Block and Salinas Blocks are separated by the Monterey Bay Fault Zone (fig. 5-3).

FAULTS

5.8. The northern portion of the area is marked by the Ben Lomond Block, which is bounded along the north and east by the northwest-southeast trending Ben Lomond Fault. The Santa Cruz Mountain Block is separated from the Ben Lomond Block by the Zayante-Vergeles Fault and Butano Fault. The Zayante Fault trends in a northwest-southeast direction and marks the contact between the Salinas-Watsonville Basin and the Santa Cruz High. In the southern part of the area from Pt. Pinos to the San Andreas Fault, the major orogenic blocks and basins consist of the blocks being uplifted on the northeastern edge and down-thrown on the southwestern edges, which gives the area a stair-step morphology with each step bounded by a fault. From southwest to northeast, the area is marked by the Carmel Valley with the Tularcitos Fault running along the southwestern edge of the valley, and the down-thrown side of the small block is on the northeastern side. The up-thrown side continues as a wedge over the onshore extension of the Monterey Penninsula. The Chupines Fault marks the down-thrown side of the smaller underdeveloped block within the Monterey Block of Ross and Brabb (1972). The Sierra De Salinas begins at the Chupines Fault and is up-thrown to the norhtheast where it is truncated by the King City Fault. The down-thrown part of the Gabilian Block is the Salinas Valley. The Gabilian Block is then truncated by the San Andreas Fault. This area is presently undergoing remapping by Greene and others, (Greene, personel communication) and new interpretations are possible.

SEISMICITY

5.9. Information on seismic activity within the study area has been compiled by Toppozada and others (1980) for events prior to 1900, and Real and others (1978), and Sherburne and others (1985) for post-1900 events. Toppozada and others data is based on newspaper accounts and Mission reports of seismic events, and their effects on man-made structures in the area. From 1900 to the present, Kilbourne and Mualchin (1979) and Sherburne and others (1985) present data that is based on instrumentation.

5.10. Reports show that prior to 1900 there were twenty six seismic events of an estimated magnitude greater than 4.0 on the Richter scale within the study area (Toppozada, 1980; Kilbourne and Maulchin, 1979; Townly and Allen, 1939), (fig. 5-4).

5.11. Seismic activity after 1900 is presented by Kilbourne (1979). Real and others (1978) shows that twenty-six events occurred of magnitudes greater than 5.0 on the Richter scale within 100 km of the study area. Sherburne (1985) presents data on seismicity of California from 1979 through 1982, his epicenter location map shows 15 events in the study area of magnitudes of 4.0 to 4.9 (figs. 5-5 and 5-6)

5.12. The data shows that seismicity within the study area is high, and has had a continuing history of seismic activity. The data presented excludes seismic events of less than 4.0, this is due to the great number of events in the study area. Because of the tectonic nature of the area and the number of faults that dissect the area, it can be assumed that seismic events will continue into the future.

STRATIGRAPHY

5.13. Greene and Clark (1979) show four composite stratigraphic columns covering the Tertiary rocks of the central Santa Cruz mountains (fig. 5-7) upper Salinas Valley (fig. 5-8) Bowen, (1965, 1969); California State Department of Water Resources, (1970) Monterey Penninsula (fig. 5-9), and northern Santa Lucia Range (fig. 5-10). Basement rocks of the area are overlain by Tertiary sedimentary rocks that range from Paleocene to Holocene in age and range in total thickness from 2,745 m in the Monterey Penninsula and northern Gabilian Range to 9,200 m in the central Santa Cruz Mountains (Greene and Clark, 1979). The Cenozoic stratigraphy is interrupted by three major unconformities. One unconformity marks the contact between the Tertiary sediments and the Cretaceous granites. An unconformity at the Eocene-to-lower-Miocene boundary marks a lengthy hiatus in the sedimentary record. At the middle-to-upper-Miocene boundary, a shallow-water transgressive sandstone overlies deeper water foraminiferal siltstone beds.

5.14. In some areas Paleozoic metamorphic rocks of the Sur Series, which consist of limestones and dolomitic roof pendents, overlie granitic basement. Large regional hiatuses exist between the late Cretaceous and lower Miocene to Paleocene. A few localities in the Monterey Bay Area have sediments that were deposited during the time the hiatuses spanned. Those sediments occur in erosional depressions; Ben Lomond, Pt. Lobos, and the Santa Cruz Mountains have Paleogene and Oligocene sediments.

5.15. The only Paleogene sediments that remain in the study area are in the Locatelli Formation, which crops out on Ben Lomond Mountain, and the Carmelo Formation, which appears in the Carmel Bay area.

5.16. The Butano Sandstone, San Lorenzo Formation, Zayante Formation, Vaqueros Sandstone, and Lambert Shale (fig. 5-11) mark the Eocene-Miocene boundary in the central Santa Cruz Mountains. These contain sediments that formations were deposited at bathyal and neritic depths. The sequence has been traced southeastward to the northern Gabilian Range.

5.17. Overlying the lower Miocene sequence is a middle Miocene transgressive basal sandstone,

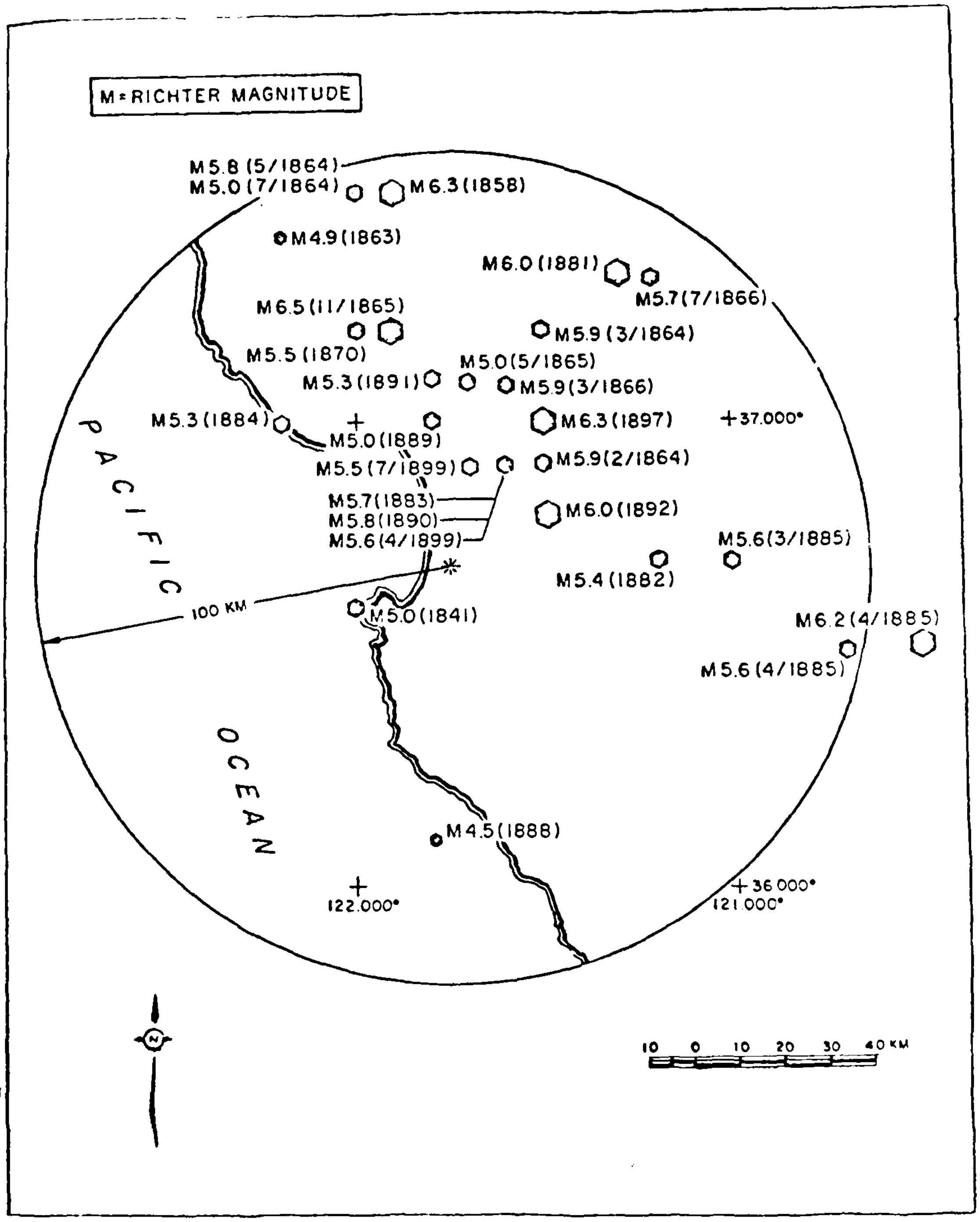


Figure 5-4. Epicenter Map of Pre-1900 Earthquakes within Salinas/Marina quadrangles [*taken from Kilbourne and Mualchin, 1979*]

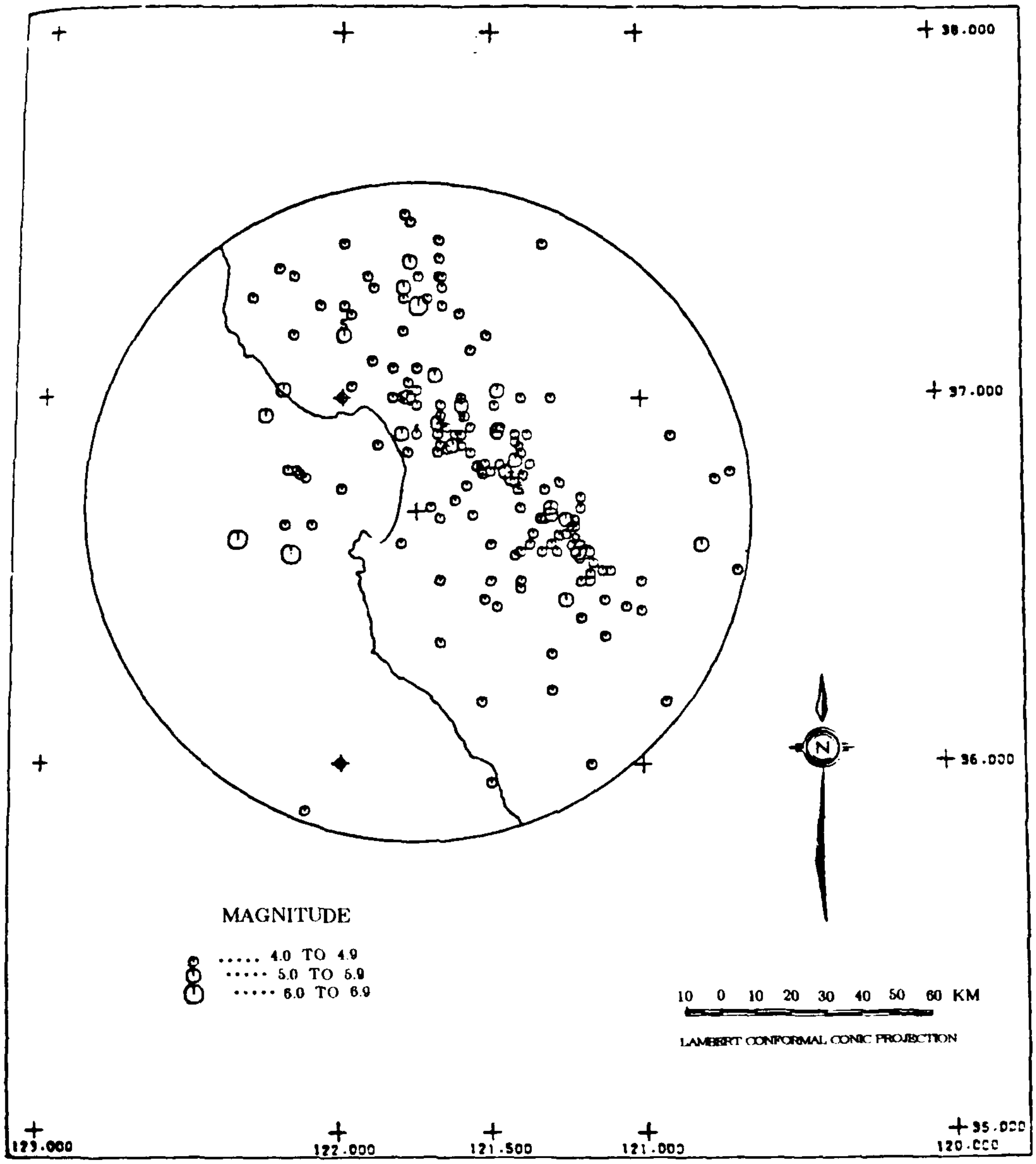


Figure 5-5. Epicenter map showing the location of seismic events for the period 1900-1974 in the vicinity of the study area (*taken from* Kilbourne and Mualchin,1979)

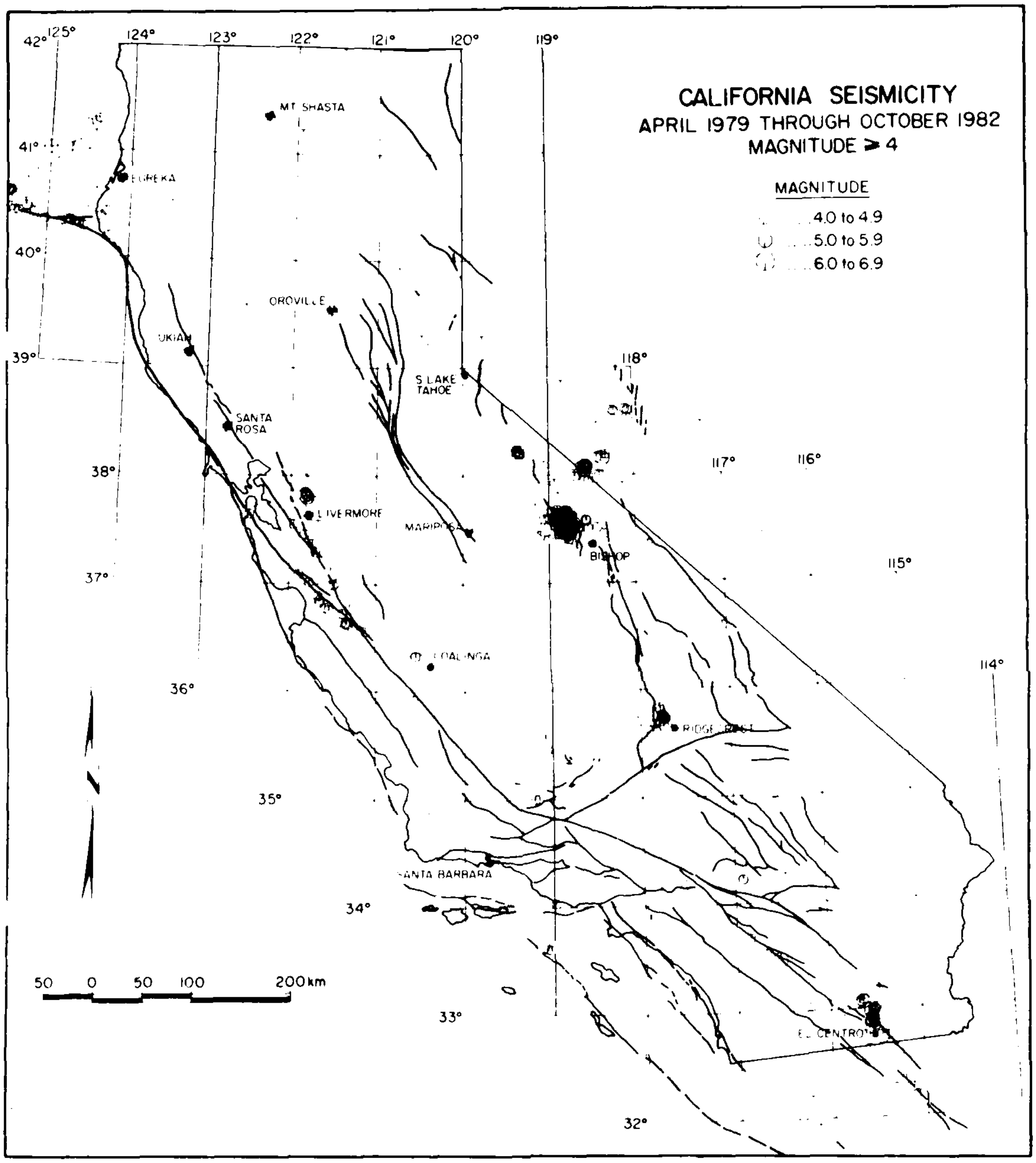


Figure 5-6. Epicenter locations of California earthquakes having magnitudes of 4.0 or greater, 1 April 1979 through 31 October 1982. [*taken from* Sherburne and Parke, 1985]

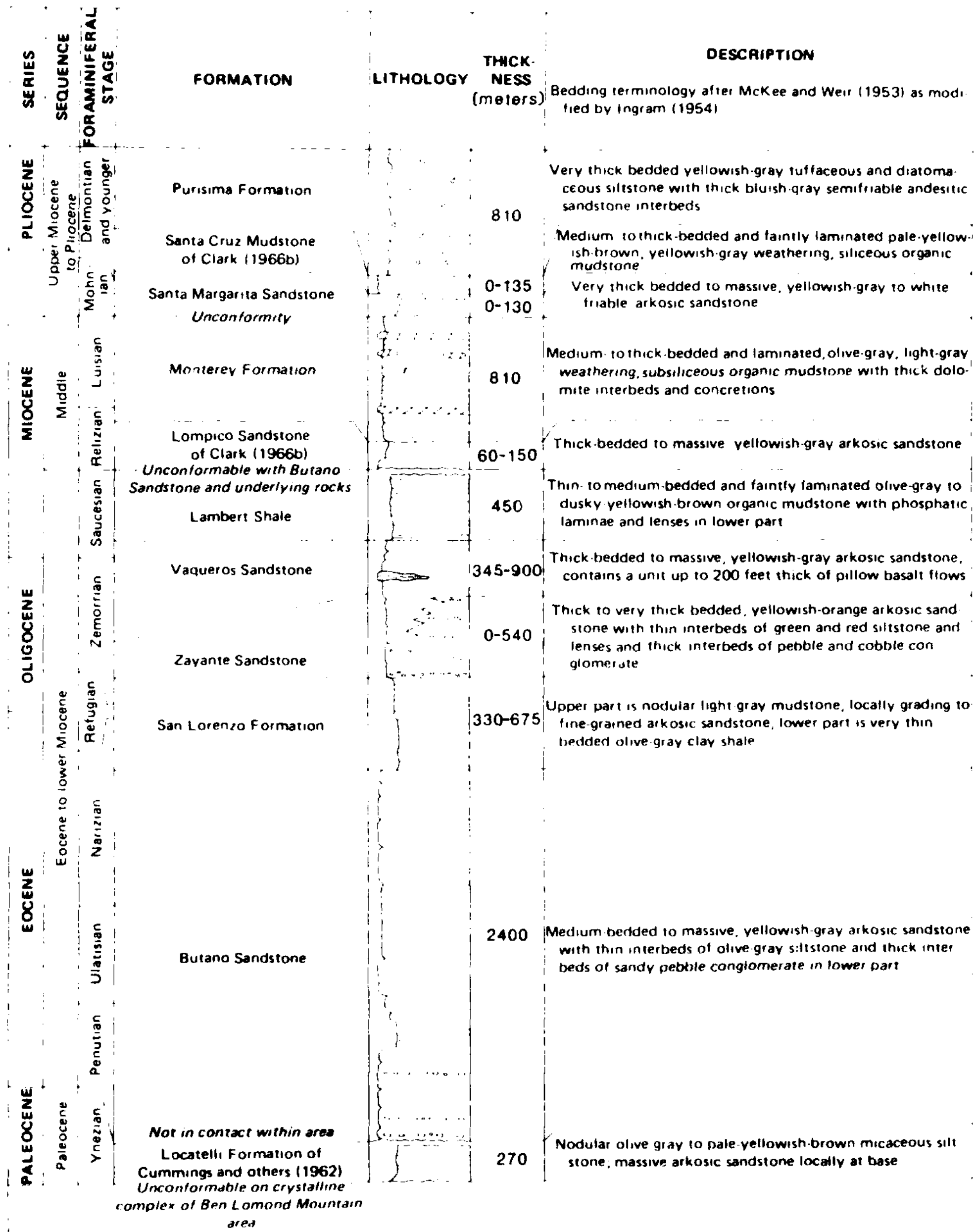


Figure 5-7. Composite stratigraphic column of Tertiary rocks of central Santa Cruz Mountains southwest of San Andreas Fault and northeast of San Gregorio fault. [*from* Clark and Rietman, 1973]

AGE	SEQUENCE	FORMATION	LITHOLOGY	THICK-NESS (meters)	DESCRIPTION
PLEIST-OCENE		Aromas Sand		90	Reddish-orange cross bedded sand; non-marine
? PLIO-CENE ?	? UPPER MIOCENE TO PLIOCENE	Paso Robles Formation		150	Old alluvium deposited in a valley. Light colored sands and gravels; non-marine.
MIOCENE	UPPER MIOCENE TO PLIOCENE	Santa Margarita Sandstone		480	White arkosic sand; minor gravel; marine and brackish marine, locally fossiliferous
MIOCENE	UPPER MIOCENE TO PLIOCENE	Monterey Formation		900	White diatomite in upper part; light brown siliceous shale in lower part
MIOCENE	MIDDLE MIOCENE	Marine sandstone (Temblor Formation of Trask, 1926)		250	Buff colored weathering arkosic sand and brown sandstone, gravel, minor shale - *marine*. Interbedded olivine basalt, vesicular or amygdaloidal.
MIOCENE	MIDDLE MIOCENE	Red beds of Robinson Canyon		150(?)	Conglomerate, arkose, minor lake-bed clay; commonly red, maroon and green; non-marine
PALEOCENE		Carmelo Formation of Bowen (1965)		330	Buff to brown sandstone with much plant debris; thick conglomerate lenses made up of granitic rocks and strongly colored volcanic porphyries; marine
CRETACEOUS OR JURASSIC		Crystalline complex		?	Granites-granodiorites and quartz monzonites, locally porphyritic.
PALEOZOIC		Sur Series of Trask (1926)		?	Dark brown quartz-mica schist and gneiss; minor crystalline limestone.

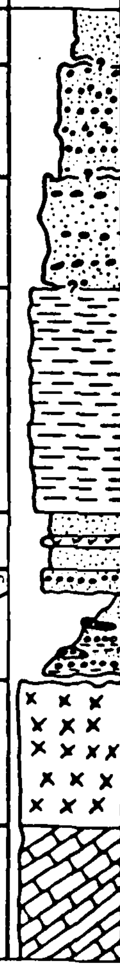


Figure 5-8. Composite stratigraphic column of upper Salinas Valley-northern Santa Lucia Range. [*modified after* Beal, 1915]

NORTHERN MONTEREY BAY REGION

AGE		SEQUENCE	FORMATION	LITHOLOGY	THICKNESS (meters)	DESCRIPTION
QUATERNARY	Holocene	Upper Pliocene to Holocene	Surficial deposits		40	Recently deposited marine sand and mud.
					240	Submarine landslide and slump material.
					50	Gravel, sand, and mud; some broken consolidated material.
	Pleistocene		Aromas Sand		300	Well sorted, cross-bedded, quartzose sand; nonmarine, eolian. Fluvial locally at base.
			Deltaic material		±40	Sand and mud; marine, deltaic.
TERTIARY	Pliocene	Upper Miocene to Pliocene	Purisima Formation		670+	Greenish-gray, semi-consolidated to consolidated sandstone, siltstone, and shale; marine, generally fossilifersous.
			Santa Cruz Mudstone of Clark (1966)		200+	Siliceous, organic mudstone; marine.
	Miocene		Santa Margarita (?) Sandstone		370?	Bedded arkosic sandstone (?)
		Middle Miocene	Monterey Formation		550	Light olive-gray, rhythmically bedded, organic mudstone, diatomaceous and siliceous shale and siltstone; marine.
MESOZOIC OR OLDER			Granitic rocks (crystalline basement)			Probably prodominantly granodiorite.

Figure 5-9. Composite stratigraphic section of the northern part of Monterey Bay, east of the Palo Colorado-San Gregorio fault zone.

SERIES	SEQUENCE	FORAMINIFERAL STAGE	FORMATION	LITHOLOGY	THICKNESS (meters)	DESCRIPTION
PLIOCENE			Purisima Formation		600	Massive yellowish to light-gray sandstone with siltstone, conglomerate, and coquina interbeds
			Not in surface contact			
MIOCENE	Eocene to lower Miocene	Saucesian	Volcanic rocks		300-420	Dacitic and andesitic flows and agglomerate with light-brown arkosic sandstone interbeds
OLIGOCENE	Eocene to lower Miocene	Zemorrian	Red beds of Kerr and Schenck (1925)		0-360	Red pebble and boulder breccia and conglomerate with interbedded red and yellow arkosic sandstone
OLIGOCENE	Eocene to lower Miocene	Zemorrian	Pinecate Formation of Kerr and Schenck (1925)		200-330	Massive yellow arkosic sandstone with a few interbeds of pebble and boulder conglomerate
OLIGOCENE / EOCENE	Eocene to lower Miocene	Refugian / Narizian / Ulatisian	San Juan Bautista Formation of Kerr and Schenck (1925)		540-1500	Poorly bedded buff sandstone and interbedded gray to dark-brown siltstone; lower part chiefly siltstone

Figure 5-10. Composite stratigraphic column of Tertiary rocks of the *Northern Gabilan Range* southwest of the San Andreas fault. [*After* Clark and Rietman, 1973].

STRATIGRAPHIC SEQUENCES FOUND IN MONTEREY BAY AREA

Period	Epoch	Offshore Northern Monterey Bay	S. Cruz Mountains North	Northern Gabilian Range	Offshore Southern Monterey Bay	Northern Santa Lucia Range	Age m.y.b.p.
Quaternary	Holocene	Surficial Deposits: -dunes -beach sand -river deposits			Surficial Deposits: -dunes -beach sand -river deposits		.01
	Pleistocene	Aromas Sandstone Deltaic Deposits			Deltaic Deposits Aromas Paso Robles Formation	Aromas Sandstone	1.6
Tertiary	Pliocene	Purisma Fm Santa Cruz MS	Purisma Fm Santa Cruz MS	Purisma Formation	Purisma Formation	Paso Robles Formation	5.3
	Miocene	Santa Margrita Monterey Formation	Santa Margrita Lompico SS Lambert Shale	Volcanic Rocks	Monterey Formation	Santa Margrita Monterey Fm Temblor Fm Red Beds	23.7
	Oligocene		Vaqueros SS Zayante Fm San Lorenzo Fm	Red Beds Pinecate Fm			36.6
	Eocene		Butano SS	San Juan Bautista Fm			57.8
	Paleocene		Locatelli Fm			Carmelo Fm	66.4
Mesozoic	Cretaceous	Granitic Rocks	Crystalline Complex		Granitic Rocks	Crystalline Complex	245
	Paleozoic					Sur Series	

Figure 5-11. Combination of the stratigraphic columns in the study area.

the Lampico Sandstone; above that is an organic mudstone, the Monterey Formation. This marine transgression trends in a northwest-to-southeast direction. The Lampico Sandstone can be traced from north of Santa Cruz, where the beds are late Relizian, in age, to the south and east where they are younger. The beds then become late Relizian to Lusian (Miocene) in Scotts Valley to Mohnian in age on the Monterey Penninsula. This sequence and the overlying upper-Miocene-to-Pliocene sequence are time transgressive. This latter sequence consists of the Santa Margarita Sandstone, a shallow water transgressive sandstone; the Santa Cruz Mudstone, a deeper water siliceous mudstone; and the shallow water Purisima Formation. These formations are not found in the southeast, but Purisima Formation crops out in the northern Gabilian Range.

5.18. Both the Purisima and Santa Margarita formations undergo many facies changes from northwest to southeast. The Purisima is missing north of Santa Cruz; it laps onto the Santa Cruz Mudstone in the southern Santa Cruz Mountains and near the city of Santa Cruz, where the contact is unconformable. The Paso Robles Formation overlies the Purisima near Moss Landing but overlies the Monterey Formation in the Monterey area and probably locally on Santa Margarita Formation.

5.19. Pleistocene and Holocene marine terrace deposits crop out along the coast. The Aromas Sand, of Pleistocene age, is exposed in the Watsonville lowland and upper Salinas Valley. This formation is composed of eolian sands; it depositionally overlies the Paso Robles Formation and locally rests on the Purisima Formation.

QUATERNARY GEOLOGY

5.20. While the Santa Cruz Structural Block has uplifted at a rate of 0.16 to 0.27 m/1,000 yrs (Bradely and Griggs, 1976) exposing deep marine sediments, the area around Watsonville has slowly subsided and filled with marine sequences that record both tectonic and glacio-eustatic sea level changes. The emergence of the area was continuous with gradual southwestward tilt for the entire structural block throughout middle-to-late Pleistocene. This was coupled with general tectonic uplift during middle-to-late Pleistocene time

5.21. The terraces at Santa Cruz and north of Santa Cruz formed from a combination of tectonic uplift and glacio-eustatic sea-level changes. Formations which were originally deposited in deep ocean basins, emerged with the Ben Lomond Mass and Santa Cruz Mountains. These sea-level fluctuations are preserved in wave-cut terraces. The lack of nearshore deposits along these terraces are due to a paucity of source material, and subsequent erosion of any deposits; similar processes are still occurring today.

5.22. Between Santa Cruz and Monterey, the Pleistocene deposits consist of valley fill, marine and valley terrace deposits, older alluvium, and older sand dunes. In the northern Gabilian Range are older alluvium and marine terrace deposits of Pleistocene age.

5.23. Dupre (1975) and Tinsely (1975) state that central and southern Monterey Bay have been regions of continuous subsidence throughout the Quaternary. Sea-level fluctuations and tectonic subsidence occurred simultaneously in the area of the Watsonville-Salinas lowland. Based on Quaternery sediments in the Santa Cruz, Watsonville, and Manresa Beach areas, Dupre, Clifton, and Hunter (1983) determined that a total of eleven episodes of sea-level rises have occurred since Pleistocene time. This figure was based on nearshore transgressive deposits that were formed by either glacio-eustatic sea-level changes or tectonic uplift or subsidence.

5.24. The basis of their hypothesis is that in areas of uplift, such as north of Santa Cruz, rising sea level produced an erosional transgression recorded largely as a wave-cut platform with a few patches of sediment. The remaining deposits occur in coastal terraces that formed during periods of falling sea level. On the other hand, in non-uplifting regions where glacio-eustatic sea-level rise is the dominant factor, the deposits record fluvial and esturine sedimentation. Extensive flood-plain and alluvial-fan surfaces form during highstands of the sea. Coastal terraces near the mouths of major rivers may also form by deltaic progradation during this time. Subtle changes in vegetation and wind patterns are recorded in marine and eolian sediments during lowering of sea level.

5.25. Dupre and others (1983) have recognized five sequences of rising sea level based on fluvial aggradational sequences in the Watsonville area. Five highstands are recognized from shoreline angles of uplifted coastal terraces. Eolian deposits seem to be the most sensitive climatic change indicator. Ten episodes of eolian activity are preserved; each is separated by a soil formation. Combining both fluvial and eolian deposits in the Watsonville area, eleven cycles of glacioeustatic sea-level changes are recorded since the emergence of Purisma Formation.

6. MORPHODYNAMIC PROCESSES

6.1. This chapter uses existing information, most of which was presented in the previous chapters, to develop a morphodynamic model that delineates the pattern of sediment dispersal in Monterey Bay. This discussion will provide a basis for future studies of sedimentary processes within the littoral zone of the bay. Because the availability and movement patterns of sand are crucial to the health of an area's beaches, the main focus of this chapter will be to define the sediment budget for Monterey Bay.

Sediment Budget

6.2. The sediment budget is a conceptual technique that uses the principle of the conservation of mass to predict changes in the volume of littoral sediments. The time rate of change of sand volume within a section of coast (or *compartment*) depends upon the rate at which sand enters the compartment versus the rate at which it leaves (Komar, 1976, p. 227). The budget involves determining the sediment contributions (from *sources*) and losses (to *sinks*) and equating the difference between them to the net gain or loss within the compartment (Bowen and Inman, 1966). A sediment gain produces accreting beaches within the compartment, and a loss produces eroding ones. Table 6-1 lists possible sedimentary sources and sinks; some of them may not be important in a given compartment.

SOURCES	SINKS
Longshore transport into the area**	Longshore transport out of the area
River transport**	Deposition in submarine canyon**
Sea cliff erosion**	
Onshore transport by waves, currents*	Offshore transport by waves, currents*
Wind transport from dune to beach	Wind transport from beach to dune*
Hydrogenous deposition	Solution and abrasion
Beach nourishment	Mining**
Biogenous deposition	

Table 6-1. Potential sources and sinks of littoral sediments (after Bowen and Inman, 1966). Double asterisks (**) mark the most important sources and sinks in Monterey Bay; single asterisks (*) mark ones that are locally important.

LITTORAL CELL

6.3. Some coastal areas divide naturally into compartments that contain a complete cycle of littoral sedimentation and transport. Inman and Frautschy (1966) describe four compartments or *littoral cells* along the southern California coast where rivers are the chief source, and a downdrift submarine canyon the chief sink (fig. 6-1). Typically, a southern California littoral cell is bounded by rocky headlands that restrict the longshore movement of sand. Rivers discharge sediment directly into the littoral zone, and the waves drive the sand fraction of that sediment alongshore. Within a typical California littoral cell, longshore transport is usually towards the south because the prevailing waves come from the northwest. Usually, the beach widens in a

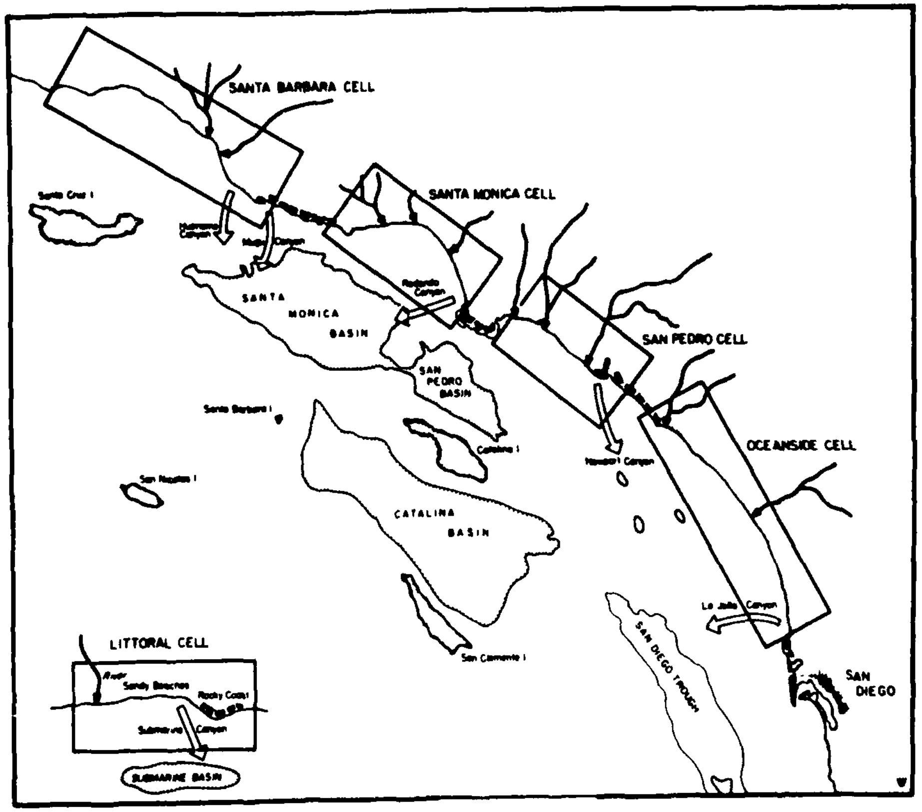


Figure 6-1. Schematic representation of littoral sedimentation along the southern California coast [from Inman and Frautschy, 1966].

downdrift direction within a cell as rivers add sand at various points, while the capacity of the longshore current to transport the sand remains essentially constant. Generally, grain size decreases downdrift except where rivers enter the cell. Eventually, the longshore-moving sand enters a submarine canyon whose head extends into the littoral zone and is lost to deep water. Estimates can be made of the amount of sand supplied to a cell and lost from it to tell whether the beaches within the cell are eroding or accreting. As long as the supply of sand stays approximately equivalent to the competence of the longshore current, the beaches more-or-less will be in equilibrium. If, over the long term, the waves become more energetic and/or the supply of sand is reduced, the beaches will erode.

Monterey Bay's Littoral Cells

6.4. Habel and Armstrong (1977) separate the California coast into five shoreline types:

1. Littoral cells that terminate at submarine canyons.
2. Deltas that are stabilized between headlands.
3. Crescent or crenulate bays.
4. Crenulate spits.
5. Parallel alignments.

The Monterey Bay shoreline falls entirely into category (1); and the bay's littoral zone is divided into two littoral cells, the Santa Cruz Cell and the Southern Monterey Bay Cell -with Monterey Submarine Canyon in-between (fig. 6-2). Each cell will be discussed in turn, focusing on the sources, transport paths, sinks, and, finally, the sediment budget. The rates cited in this chapter are only estimates; the only measured measured sediment transport rates come from Santa Cruz Harbor, which trapped all the littoral drift for at least two years after it was built.

SANTA CRUZ CELL

6.5. Habel and Armstrong (1977, p. 4) set the boundaries of the Santa Cruz Cell at Point Santa Cruz in the north and Monterey Canyon in the south; however, the updrift end of the cell may be as far north as the entrance to San Francisco Bay (Inman, 1976, p. 110). As with most of the littoral cells along the California coast, net transport is from north to south in the Santa Cruz Cell.

Sources

6.6. Using Point Santa Cruz as the cell's northern boundary, the major sources of littoral material for the Santa Cruz Cell are (in decreasing order of importance):

1. littoral drift from the north;
2. rivers, especially the San Lorenzo and Pajaro;
3. eroding coastal cliffs.

Estimates based on wave studies (Anderson, 1971; Seymour and others, 1978; Walker and others, 1978) and direct measurements of sedimentation at Santa Cruz Harbor (Moore, 1970; Walker and Williams, 1980) put the average littoral drift at 200,000 m^3/yr for Santa Cruz, though the uncertainty in that figure may be as much as a factor of two (Hicks, 1985, p. 16). For a given year transport is usually very episodic, with almost half of the annual transport occurring during 10% of the time in the winter months (Seymour and Castel, 1984). When averaged over a year or two, the transport rate may seem fairly steady because the episodic events are filtered out (Hicks, 1985, p. 3).

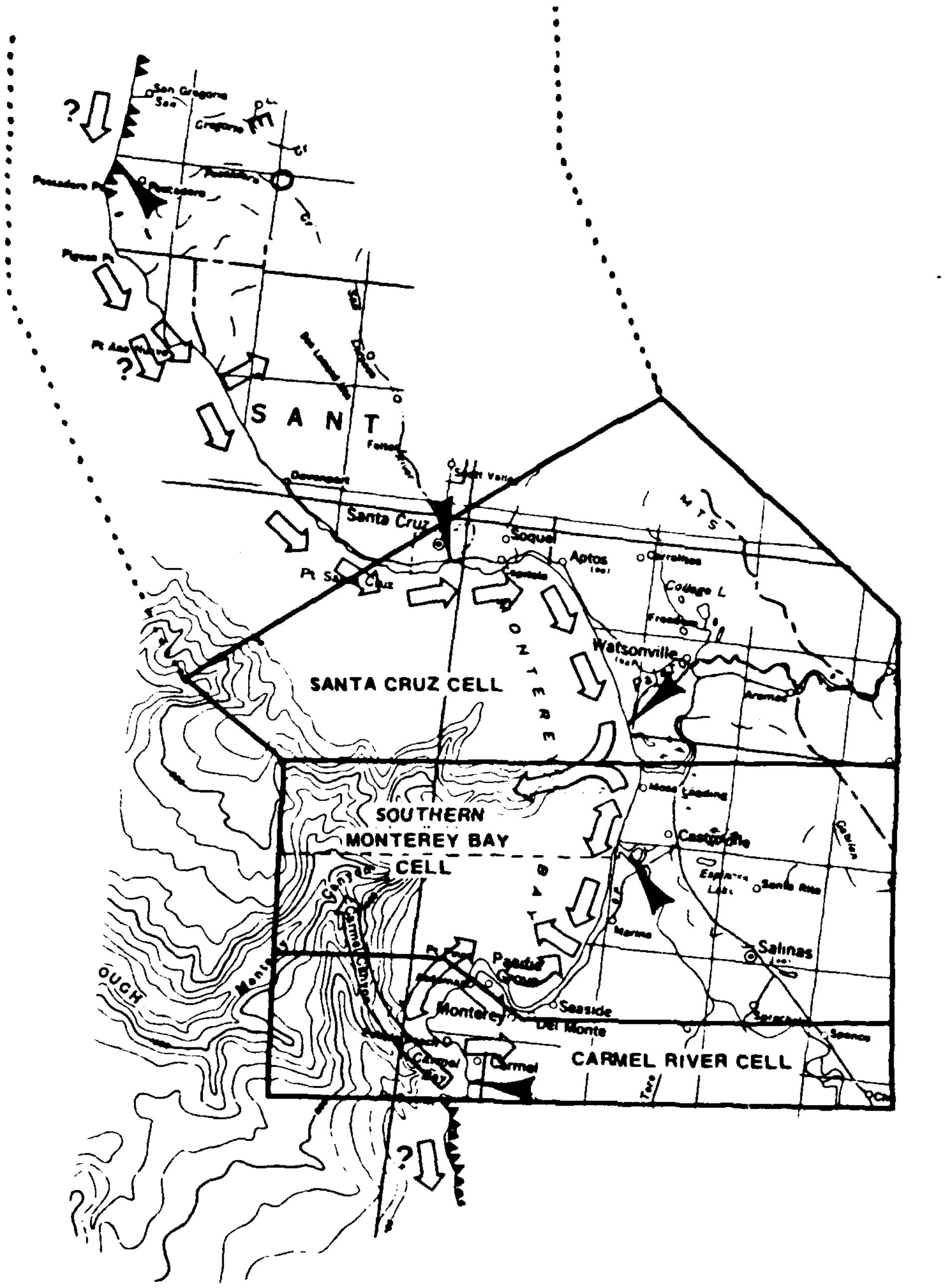


Figure 6-2. Chart of Monterey Bay showing the locations of the Santa Cruz and Southern Monterey Bay littoral cells [*adapted from* Habel and Armstrong, 1977, p. 23]. The dotted lines mark the area that could be included in the Santa Cruz Cell because there is a large component of sand moving into the northen end of cell along the shore. The dashed line delineates an area that could be a separate cell because of divergent transport directions at the mouth of the Salinas River.

6.7. As shown in the *Basin Sediment Resources* Chapter, river-supply estimates vary greatly. Compared to littoral transport, river supply is very irregular, and the yearly totals fluctuate significantly (Hicks, 1985, p. 2). For example, a common estimate for the average sand-sized discharge rate for the San Lorenzo River is around 60,000 m^3/yr. Hicks showed that material with grain sizes less than 0.18 mm leaves the littoral system at the river mouth; therefore, he lowered the supply rate for the San Lorenzo River to 30,000 m^3/yr. The actual annual discharge may be a small percentage of that figure during mild years, and several times it during the occasional very rainy years.

6.8. Total sediment discharge estimates for the Pajaro River range from 136,000 to 382,000 m^3/yr. The other streams that empty directly into the ocean (such as Soquel and Aptos Creeks) supply significantly less sediment than either the San Lorenzo or Pajaro Rivers. The total amount of sand-sized material supplied to the littoral zone of the northern Monterey Bay littoral cell is probably around 200,000 to 300,000 m^3/yr, though the average could be off by a factor of two, and the actual amount of sand supplied in a given year may differ by even more.

6.9. One estimate of cliff-erosion rates in the northern Monterey Bay littoral cell is around 75,000 m^3/yr. Again, as with river sediment input, cliff erosion is episodic. Only in very stormy winters, like 1977-78 and 1982-83, is enough sand removed from the beach for the waves to directly attack the cliffs. Also, in northern Santa Cruz county, the sea cliffs are primarily mudstones (Griggs and Johnson, 1976), which contribute little sandy material to the littoral zone.

Transport Paths

6.10. The net longshore transport for the northern Monterey Bay littoral cell is from Point Santa Cruz to Monterey Canyon. Most wave directions produce downcoast transport throughout the cell, but there are some sections of the shoreline where the transport direction reverses for certain wave directions (see the 'Littoral Drift' section in the *Littoral-Zone Resources* chapter). Those reversals, however, are temporary and do not affect the sediment-budget estimate for the cell, but they are important in terms of maintaining beaches in the Santa Cruz-Capitola area.

Sinks

6.11. In the Santa Cruz Cell sand is lost to Monterey Submarine Canyon, the offshore, and the coastal dunes. Some sand may be blown ashore into the dune fields in the southern part of this cell, but very little of the dune field between La Selva and Moss Landing is active now (Cooper, 1967, p. 65-67). Arnal and others (1973) calculated that 30,000 m^3/yr of sand was lost to the dunes throughout the bay and that about three percent of that total occurred north of Monterey Canyon. There is no good estimate of how much sand is lost to the offshore; however, the shoreline within the cell has prograded somewhat over historical time except in the area between the San Lorenzo River and Soquel Creek and just north of the Pajaro River (U. S. Army Corps of Engineers, 1958).

6.12. The lack of other major sinks indicates that essentially all of the 500,000 m^3/yr of sand moving along the shore either moves into the Southern Monterey Bay Cell or enters Monterey Canyon when it reaches the southern end of the cell. Yancey (1968), Wong (1970), and Davis and others (1966) concluded that essentially no sand bypasses the canyon head. Therefore, all the sand enters the canyon head and eventually ends up on the Monterey Fan (Wilde, 1965). Yancey found no glaucophane south of the canyon, indicating that sand from the Pajaro River does not bypass the canyon. Davis and others found that dyed sand injected south of Moss Landing always moved north toward the canyon. Wong suggested that the combination of northward transport caused by wave refraction over the canyon head and a seaward-flowing current on the north side of the north jetty at Moss Landing would force the southward-moving sand to move offshore and into the canyon before reaching the entrance to Elkhorn Slough. It appears that constructing the north jetty altered the natural transport pattern by producing a hydraulic flow that moves the sand offshore. Based on dyed sand tracer experiments in the vicinity of the canyon head, Arnal and others (1973) concluded that most of the sand reaching Monterey Canyon from the north bypasses it and continues to move south. In their experiments, dyed sand injected just north of the north jetty at Moss Landing was found south of the canyon head. Based on their observations, they estimated that only 31,000 m^3/yr moved into the canyon. Perhaps both arguments have merit: sand directly onshore of the canyon head moves south to some extent, but the southward moving sand in the northern cell moves seaward and into the canyon before it reaches the head.

Budget and Problems

6.13. Very approximately, the total longshore transport rate in the recent past has been 200,000 m^3/yr at Point Santa Cruz, 230,000 m^3/yr at Capitola, and 500,000 m^3/yr at the head of Monterey Canyon. Griggs (Oral comm., 1985) stated that in historical times the Monterey Bay coastline from New Brighton Beach to Del Monte Beach has been stable. In fact, the wide, sandy beaches and extensive sand dunes suggest that the sand supply has exceeded the minimum needed to maintain an equilibrium shoreline. In the last few years, however, the coastline has started to retreat again.

6.14. Moreover, even though the shoreline in the northeast corner of the bay has generally prograded in historical times, there are erosion problems associated with when littoral transport takes place. The U. S. Army Corps of Engineers (1958) concluded that the littoral drift in the northern Monterey Bay littoral cell was sufficient to maintain the eastern beaches, but that the sand moved so quickly along the Point Santa Cruz to New Brighton Beach stretch of coast that beaches could not form, especially in the winter. Only east of south-facing headlands did substantial beaches form. Griggs and Johnson (1976) pointed out that erosion occurs east of Santa Cruz Harbor because of *when* the littoral drift occurs. In the winter, Santa Cruz Harbor fills in, trapping 30% of the annual littoral drift. This sand is not reintroduced to the littoral zone until spring when the harbor is dredged. Therefore, in the late winter and early spring there is a net deficit of sand east of the harbor. As this is the time of year when storms can be expected, there is more erosion than before the harbor was built even though the average-annual littoral drift rate is the same.

6.15. Actually, the littoral drift rate may be less than even ten years ago. Weber (Oral comm., 1985) thinks that the volume of sand entering the cell from the north has decreased substantially over the last several years. He thinks that erosion along the northeast shoreline was substantial up to about 200 years ago. At that time the large dune field to the north at Año Nuevo started to erode, injecting large volumes of sand into the littoral zone each year. That extra sand was sufficient to stabilize the east-shore beaches. Now, however, the dune field has essentially disappeared, and littoral drift into the northern Monterey Bay littoral cell has returned to its pre-historical rate. Thus, there is insufficient sand for the beaches along the northeast shore, and they have started, again, to retreat.

SOUTHERN CELL

6.16. The southern Monterey Bay littoral cell starts at Point Piños and ends at the head of Monterey Canyon (Habel and Armstrong, 1977). This cell is unusual because the only river entering it–the Salinas River–is adjacent to the canyon head, and the littoral drift is away from the canyon in the center of the cell. This pattern suggests to us that littoral processes south of Monterey Canyon would be better understood if the area were divided into two cells with one extending from the Salinas River to the canyon and the other from the river to the Monterey Peninsula (fig. 6-2). In the following discussion, we will keep with the traditional cell boundaries; however, we will point out why the concept of two sub-cells has merit.

Sources

6.17. The sources of littoral-zone sediment in the southern Monterey Bay littoral cell include the Salinas River, coastal dunes, and offshore sands. Longshore transport into the cell is insignificant because Monterey Canyon intercepts southward-moving sand (see above for another opinion), and Point Piños is a barrier to sand that would enter the area from the south. Furthermore, the prevailing northwest winds would drive littoral sand south from Point Piños.

6.18. The Salinas River supplies an average of between 30,000 and 765,000 m^3/yr of material to the coast (see table 3-4). The low value came from Welday (1972) and applied to medium-to-coarse sand only. The upper value came from Dorman (1968) and was based on growth of the Salinas River delta since its lower channel was fixed in 1908. However, there are still questions about how much of the material in the Salinas delta is recent. Yancey (p. 8) thought that its shape suggested that much of the delta formed in earlier times when it was above sea level. He concluded that the location of the canyon and the Salinas River mouth have remained in the same place during the Pleistocene and Holocene (p. 87). Gordon (1979, p. 231) cited studies that suggest that the mouth has been at its present location for long periods of time. In a study of the Salinas delta, Chin (1984) found three major subbottom reflectors; one restricted to the outer and middle shelf, and the other two extended to shore. In the second zone he saw prograding foresets, suggesting that the fan sediments were deposited during regressions of the sea. The reflectors or unconformities indicate transgressive periods. He concluded that the upper eight meters of sediment on the delta were deposited during the Holocene and the bottom eight meters were deposited during the Pleistocene.

6.19. Arnal and others (1973) present two average sediment-discharge values for the Salinas River: 439,000 m^3/yr before 1957, and 285,000 m^3/yr after 1957 when the dams were completed upriver. As with the San Lorenzo River, the amount of material supplied to the coast by the Salinas River varies significantly from year to year (see fig. 3-5). In years of low discharge, most of the sediment remains in the river; in years of high discharge, the sediment flushes into the bay.

6.20. The bluffs of Flandrian and pre-Flandrian dune sand in southern Monterey Bay supply approximately 340,000 m^3/yr of sand to the littoral cell. This estimate is very rough; the value is based on an average retreat rate of approximately 2 m/yr. Again, those bluffs only erode during times of intense storms such as occurred during the winter of 1982-83 (Dingler and others, 1985). Combellick and Osborne (1977) concluded that erosion of the coastal dunes and onshore migration of relict or modern offshore surface deposits were the most important sources of beach sand in southern Monterey Bay. No one, though, has estimated how much sand comes from the offshore sand deposits. The actual mechanism for such onshore movement is not clear either. For example, the outer coarse-sand body described by Dorman is in a water depth of 20 m except off Sand City where it extends to shore (and, therefore, is already part of the littoral zone as defined in the chapter on Littoral-Zone Resources). Dorman suggested that the coarse sand moved offshore at Sand City, rather than onshore. Wave processes acting along the beaches would not generally move coarse sand onshore, and the slow rise in sea level would leave the deposits in deeper water with time. Therefore, it seems best to not assign any annual supply rate to the offshore sand, but to remember that it may be important along some parts of the southern Monterey Bay coast.

6.21. Relatively little sand is blown into the littoral cell by offshore winds. Arnal and others think that less than 8,000 m^3/yr are blown from the fringing dunes to the beach. This is primarily because offshore winds in excess of 26 km/hr, the velocity needed to move sand effectively (Cooper, 1967), are uncommon in Monterey Bay (Arnal and others, 1973, p. 8).

Transport Paths

6.22. Whereas the longshore drift in the northern Monterey Bay littoral cell was almost entirely downcoast, there is both significant upcoast and downcoast drift in the southern cell. Along the Monterey Peninsula, any longshore transport, of which there is apparently very little, would be from west to east. Monterey Harbor blocks any longshore transport from the Peninsula to the bay's eastern shore.

6.23. From Monterey to Sand City sand moves upcoast. Galliher (1932) showed that the wind and grain-size patterns were consistent with upcoast transport in this area. Dorman (1968, p. 73) concluded that wave and current patterns in the southern part of the bay produced northward albeit small, transport there. Sayles (1966) cited the high hornblende concentrations in the heavy minerals from this area as evidence that there was no transport into this area from the north.

6.24. Between the Salinas River and the southern boundary of Fort Ord, southward transport predominates. However, the rates may be fairly small. Johnson (1953) explained that a large refraction coefficient reduced the wave height but increased the rate of longshore drift; however, a small refraction coefficient did the opposite. Therefore, the largest waves along a section of coast mark the region where the longshore drift is least. When this concept is applied to southern Monterey Bay, the region of small-to-zero littoral drift is in the center of Fort Ord. Galliher's data support this as do field observations by Sallenger (oral comm., 1985). In conclusion, there is downcoast longshore transport south of the Salinas River. The transport rate decreases to the south, reaching zero somewhere between the northern boundary of Fort Ord and Sand City.

6.25. North of the Salinas River, transport can be either to the north or to the south, depending on the wave direction. Arnal and others think that there is net southerly transport in this area. Combellick and Osborne think that the Salinas River is a minor supplier of sand to the Fort Ord area, suggesting that river sand must move north. It seems that timing is important in determining whether the net transport direction is north or south. Most of the sand supplied by the Salinas River reaches the coast during times of intense flooding, when the storm tracks are south of the normal line. Thus, newly delivered sand is subject to strong northward transport. Later, when southward transport persists, the Salinas River is not delivering sand to the bay, so the amount of sand moved may be less.

Sinks

6.26. Monterey Submarine Canyon is the principal sink for sand from the Salinas River, though some of that sand also contributes to the observed growth of the fan. In fact, fine sand entering the bay during floods may be carried directly into deep water by the strong jet coming out of the mouth of the river. Roughly, the amount of sand lost may be as high as 500,000 m^3/yr (Welday, 1972), or as low as approximately 30,000 m^3/yr (Arnal and others, 1973). It seems that a rate of 100,000 to 200,000 m^3/yr may be a good ball-park figure.

6.27. Other sinks in southern Monterey Bay include sand mining, onshore transport by wind, and offshore transport by waves. The exact amount of sand mined in southern Monterey Bay is not known (see the chapter on Littoral-Zone Resources), but is probably at least 230,000 m^3/yr. Arnal and others estimate that about 30,000 m^3/yr is moved onshore by winds, which is almost an order of magnitude less than the estimate by Dorman (which is very shaky!). Loss to the offshore by waves could be about 100,000 m^3/yr (Dorman, 1968, p. 153), but that value is very rough.

Budget and Problems

6.28. The sediment budget for the southern Monterey Bay littoral cell is not well known. It appears that most of the sand delivered to the bay by the Salinas River is lost to the Salinas delta or to Monterey Canyon. That is the reason for calling the area between the Salinas River and the canyon a littoral cell. Before dams were built on the Salinas River, more sand may have reached the bay, and some of that sand may have moved south. However, in historical times before 1908, all the sediment from the Salinas River moved directly into Monterey Canyon because the mouth of the river was north of Elkhorn Slough.

6.29. Between the Salinas River and Monterey, the coast is eroding at a rate of approximately 2 m/yr. Since the amount of sand mined is about equal to the amount supplied by bluff erosion, the loss of sand to the offshore may be small.

Human Impact on Monterey Bay

6.30. Large stretches of the Monterey Bay coastline are now eroding. As elsewhere along the California coast, the volume of sand supplied to Monterey Bay's littoral cells has diminished, and increasing human impact directly on the littoral zone has modified the natural transport pathways. Where population density is high, steps have been taken to arrest coastal erosion; where it is low, little has been done, and, possibly, activities have been permitted that accelerate shoreline retreat. Figure 6-3 generalizes the actions man has taken to modify Monterey Bay's shoreline and the affects that those actions have had on the coastline. As population around the bay increases, there will be more pressure to stabilize the shore. Because the average amount of power dissipated in the littoral zone will remain constant for the foreseeable future, coastline stabilization will require either armoring more and more of the coast or finding new sources of sand that can be incorporated into the littoral transport system.

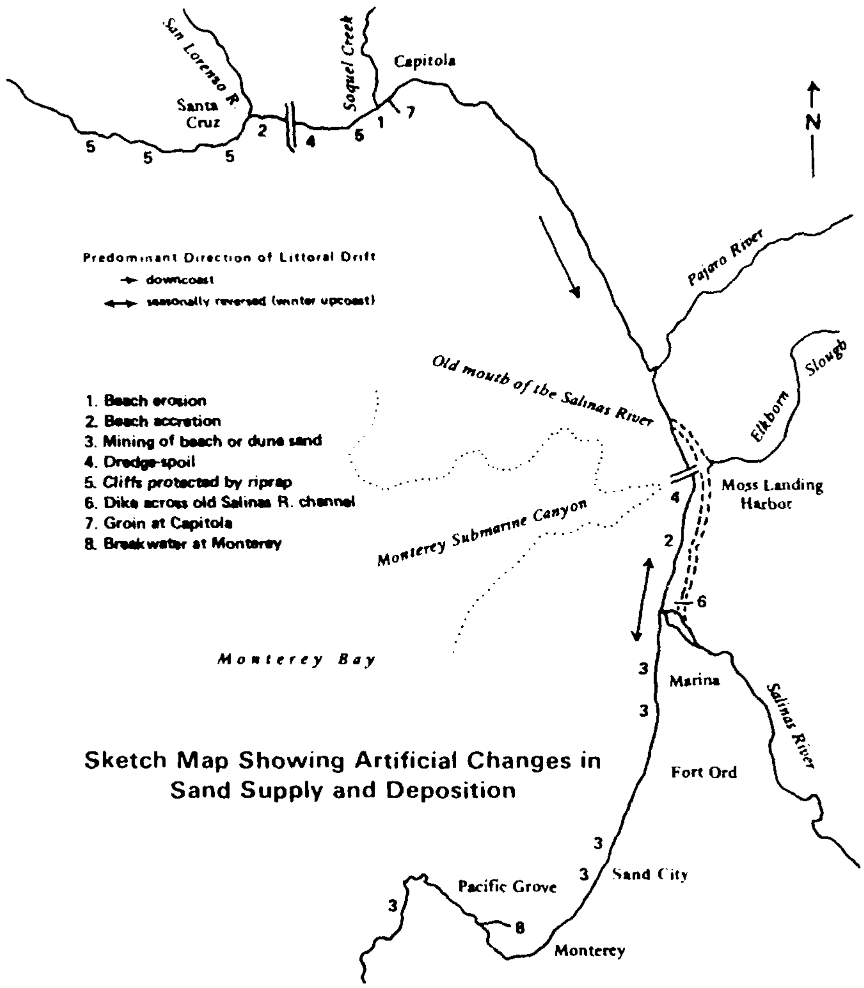


Figure 6-3. Sketch map showing artificial changes in sand supply and deposition along the Monterey Bay coast [*from* Gordon, 1979, p. 250].

7. RECOMMENDATIONS

7.1 The following is a list of recommendations for future studies. For the most part the studies are separated into field experiments that could be carried out individually; however, a clear a better understanding of the sediment budget within Monterey Bay will not be possible without completing many of the studies.

7.2 The only quantitative estimates of littoral drift come from the Santa Cruz area where Santa Cruz Harbor traps the longshore-moving sand and detailed surveys of the San Lorenzo River delta give good supply rates for two stormy seasons. Quantitative sand-budget estimates for the rest of Monterey Bay, though important to understanding morphodynamic processes, will be quite difficult to measure. Quantitative estimates of the rate of sand movement, however, could be measured. Foreshore and nearshore surveying, conducted at established locations several times a year would provide data on the rate of sand movement along the beaches (longshore transport) and to offshore areas (cross-shore transport and movement into Monterey Submarine Canyon).

7.3 **Depth of Active Sediment Transport:** The distributions of recent and relict sand should be determined. That information could be used to determine the maximum water depth that littoral-zone processes are operating today and might help answer the question of whether or not the offshore is a sink and/or source of beach sand. This study would involve coring throughout the shallow parts of the bay, geophysical surveys, and textural and heavy-mineral studies. Emphasis in the heavy-mineral studies would be on finding minor constituents that could give information on age or source.

7.4 **Expansion of the Santa Cruz Cell to the North:** This must be done to determine the source of the material moving into the bay from the north coast. Weber's hypothesis that Año Nuevo is a now-depleted point source of sand needs to be verified and other sand sources, if any exist, need to be identified. Studies of transport around headlands should be undertaken to see if littoral sediments can actually move downcoast from San Francisco. Techniques to answer these questions would include coring, side scan surveys near headlands to find pathways, and sedimentological studies at headlands that have both granitic and Franciscan rocks (e.g., Pillar Point).

7.5 **Episodic Nature of Sediment Input:** This would include studies of sand input from the rivers and cliffs. The yearly output of sandy material from the San Lorenzo, Pajaro, and Salinas Rivers needs to be determined more accurately. This requires that gaging stations be set up near the river mouths and maintained for several years to evaluate the variability of sand supply. Aerial photographs and rods placed in and near cliff faces (repeatedly measured from a stable benchmark) could be used to evaluate cliff erosion. The relationship between intense storms and both sediment discharge and cliff erosion needs to be studied in more detail. The *object in both these areas would be to quantify the supply rates for specific years.* Emphasis would be on both the maximum and the average rates.

7.6 Several site-specific studies would provide valuable information on littoral processes in Monterey Bay. Many of these studies should be carried out in the southern part of the bay where erosion rates are highest.

7.7 **Distribution and Nature of the Coarse Sand Patches in Southern Monterey Bay:** A monitoring study using side-scan sonar and emplaced rods would show how the coarse sand moves during different times of the year. The main objective of such a study would be to see if those patches are sinks for or sources of modern sand or are relict. Those coarse-sand patches might be used for beach nourishment or as an alternative source of sand for the mining companies to tap, both of which might help reduce the erosion rates along that section of coast.

7.8. **River-suplied Sediments:** Detailed grain-size analyses of the river sediments that actually reach the coast must be conducted to determine how much of the river-supplied sediments stay in the littoral zone. This study could be combined with the river study mentioned above.

7.9. **Inland Sand Mining:** A complete evaluation of the quantity and characteristics of the sand removed by the inland sand mining companies must be performed to assess the effects of this mining on the supply of sand to the bay. The implication is that the impact is minor, but this has not been completely verified.

Other Studies

7.10. **Ultimate Source of Beach Sand:** Can the ultimate source of the beach sands be determined accurately? If so, it would provide a better estimate of the relative importance of the various drainage basins.

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9. GLOSSARY

Basement Rock	The undifferentiated complex of rocks that underlies the rocks of interest in an area.
Bathyal	Pertaining to the ocean environment or depth zone between 200 and 2000 meters; also, pertaining to the organisms of that environment.
Cretaceous	The final period of the Mesozoic era (after the Jurassic and before the Tertiary period of the Cenozoic era), thought to have covered the span of time between 136 and 65 million years ago; also, the corresponding system of rocks.
Facies	The aspect, appearance, and characteristics of a rock unit, usually reflecting the conditions of its origin; especially as differentiating the unit from adjacent or associated units.
Hiatus	A break or interruption in the continuity of the geologic record, such as the absence in a stratigraphic sequence of rocks that would normally be present but either were never deposited or were eroded before deposition of the overlying beds.
Luisian	North American stage: Miocene (above Relizian, below Mohnian).
Miocene	An epoch of the upper Tertiary period, after the Oligocene and before the Pliocene; also, the corresponding worldwide series of rocks.
Mohnian	North American stage: Miocene (above Luisian, below Delmontian).
Neogene	An interval of time incorporating the Miocene and Pliocene Tertiary period; the upper Tertiary.
Neritic	Pertaining to the ocean environment or depth zone between low-tide level and 100 fathoms, or between low-tide level and approximately the edge of the continental shelf; also, pertaining to the organisms living in that environment.
Orographic	Pertaining to mountains, especially in regard to their location and distribution.
Prophyritic	The texture of an igneous rock in which larger crystals (phenocrysts) are set in a finer groundmass which may be crystalline or glassy or both.
Paleogene	An interval of geologic time incorporating the Paleocene, Eocene, and Oligocene of the Tertiary; the earlier Tertiary.

Paleozoic	An era of geologic time, from the end of the Precambrian to the beginning of the Mesozoic, or from about 570 to about 225 million years ago.
Phenocrysts	A term suggested by J. P. Iddings, and widely used, for a relatively large, conspicuous crystal in a prophyritic rock.
Recent	Holocene;the period of time since the last ice age (10,000 years in North America).
Relict	A residual topographic feature (the processes which formed the feature are no longer occurring at that location).
Relizian	North American provincial stage: Miocene (above Saucesian, below Luisian).
Siliceous	Describes a rock containing abundant silica, especially free silica rather than as silicates.
Time Transgressive	Said of a rock unit that is of varying age in different areas or that cuts across time planes or biozones; e.g. said of a sedimentary formation related to a narrow depositional environment, such as marine sand that was formed during an advance or recession of a shoreline and becomes younger in the direction in which the sea was moving. Syn: diachronous
Unconformable	Said of strata or stratification exhibiting the relation of unconformity to the older underlying rocks; not succeeding the underlying rocks in immediate order of age or not fitting together with them as part of a continuous whole.
Wrench Fault Tectonics	A term used by Greene (1977) to describe the nature of faulting associated with tectonic offset in the west coast of North America. Lateral faults in which the fault surfaces are more-or-less vertical.

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