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SUBMARINE GEOLOGY OF
SANTA MONICA BAY, CALIFORNIA

by

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SUBMARINE GEOLOGY OF SANTA MONICA BAY, CALIFORNIA

INTRODUCTION

Marine scientists at the University of Southern California began an oceanographic survey of Santa Monica Bay, California in June 1955, utilizing the facilities of the Allan Hancock Foundation for Marine Research. One of the major phases of the investigation involved a study of the topography, geology, and bottom materials of the sea floor. Interest in the bathymetry centered around the need for locating regions which were essentially free of significant relief, so that each submarine outfall pipe could be laid without excessive excavation.

A study of the bottom material was necessary to allow proper engineering design of the pipes, for the construction would have to be accomplished on material ranging from rock and gravel to fine sediments with appreciable clay content. It was necessary to investigate the subsurface sediments, because significant vertical changes in lithology are known to occur in short distances in shelf areas. Thus, borings, jettings, and cores were taken to determine the nature of the subsurface material.

PREVIOUS WORK

When making a marine geological investigation of an area such as Santa Monica Bay, pertinent information may be gained by examining the geology along the adjacent coastal region. Sediments derived from mountains, the coastal plain, and sea cliffs may be transported long distances before being deposited on the

sea floor. Studies of the source area and the transport of sedimentary particles therefore lead to a better understanding of the sea floor. Also a knowledge of the surface and subsurface geologic structures on land is helpful when attempting to decipher the structure, physiography, and history of the shelf area.

The literature dealing with Santa Monica Bay can be divided into several categories:

A. Offshore area (including the shelf, but excluding the nearshore zone) covering the subjects of submarine topography, bottom materials, geologic history, paleogeography, and structure.

B. Nearshore zone (including beaches and sand dunes) covering the subjects of beach and nearshore processes, and sediments.

C. Land geology.

In the following literature summary, an attempt has been made to indicate the most important articles for each particular phase of the marine geology of Santa Monica Bay. Additional pertinent references are in the bibliography at the end of this report and in the annotated bibliography.

Offshore Area

Blake (1856), although not describing Santa Monica Bay specifically, made one of the earliest studies of the submarine topography off the southern California coast. George Davidson (1887, 1897) while associated with the U. S. Coast Survey (later called the U. S. Coast and Geodetic Survey) gave the earliest description of submarine canyons off the California coast. W. S. T. Smith (1902) discussed California's submarine canyons, but after this date little was written until F. P. Shepard became

interested in them in the early 1930's. Three submarine canyons are located in Santa Monica Bay although one, Dume Canyon, is outside the area of this investigation. Shepard and Emery (1941) described and discussed the various theories proposed for the origin of submarine canyons, and covered in detail the submarine topography off the California coast. Recently, Crowell (1951, 1952) proposed an origin for submarine canyons using the Santa Monica Bay area as an illustration of his hypothesis. Clements and Emery (1947) studied submarine topography in relation to the distribution of earthquakes off the coast of southern California.

The earliest source of information regarding the character of bottom material in Santa Monica Bay appears on "smooth sheets" of the U. S. Coast and Geodetic Survey. The first reconnaissance survey of Santa Monica Bay was made in 1851. However, detailed work was not started until 1873 and was completed two years later. There was additional work in 1893, 1925, 1926, 1928, and an almost complete resurvey of Santa Monica Bay in 1933-34. Notations of the bottom character were recorded on the "smooth sheets" in connection with sounding operations. Bottom sediment charts compiled from these notations may show an exceptional amount of detail, e.g., U. S. Coast and Geodetic "smooth sheet" no. 1341-B made in 1875 for the northern part of Santa Monica Bay.

Trask (1931) made one of the earliest environmental studies of sediments in relation to submarine topography. Most of the samples he collected in Santa Monica Bay were located near Point Dume. The results of his study have been quoted in numerous articles and books dealing with source sediments for petroleum and the origin of oil.

The only previous quantitative studies of the sea floor of Santa Monica Bay were made by MacDonald (1934), and Shepard and MacDonald (1934, 1939). Approximately 200 bottom samples were collected, from which 139 mechanical analyses and 27 heavy mineral determinations were made. These writers also made use of U. S. Coast and Geodetic Survey chart notations and, to a minor extent, information supplied to them by fishermen. A detailed study of the sediments, changes in bottom character, interpretation of cores collected in the nearshore region, and the source of the sediments of Santa Monica Bay were discussed. The general results of this paper were summarized by Revelle and Shepard (1939), and were used by Emery (1952) for interpreting and comparing different types of sediments off the coast of southern California.

Cohee (1938) described sediments taken from submarine canyons off California including a few samples collected from the canyons in Santa Monica Bay. Dietz and Emery (1938a, 1939b); Dietz, Emery, and Shepard (1942); Emery (1941, 1947, 1952, 1954b, 1955); Emery and Dietz (1950); Emery and Shepard (1941, 1945); Emery and Terry (1956); Shepard (1934, 1937, 1939, 1940, 1941, 1948, 1951), have contributed much information to our knowledge of continental shelf sediments, areas of nondeposition, phosphorite, and other important data on sedimentation off the coast of southern California. Zalesny (1956) has studied the Foraminifera of Santa Monica Bay. Marlette (1954) in addition to a study of the nearshore sediments in the vicinity of Redondo Beach, collected several cores along the axis of Redondo submarine canyon.

Gutenberg, Richter, and Wood (1932) made a special investigation of an especially strong earthquake that took place in Santa Monica Bay in August 1930. Corey (1954), Emery (1955), have contributed to our knowledge of the structure, lithology, and paleogeography of southern California's continental borderland.

Coastal Region

Many articles have been written on various problems of the coastal region of Santa Monica Bay. Some are technical, but most are "popular accounts" of beaches, recreation, beach planning, etc. Only the references which appear to be of some interest in connection with the present investigation are included here, but additional references will be found at the end of this report. For a detailed list of all known references on the coastal as well as the offshore area, and articles of general interest, the reader is referred to the bibliography compiled by Terry (1955).

The most detailed and complete report of the beaches in Santa Monica Bay was written by Handin (1949). Handin also summarized several unpublished reports and included an excellent bibliography on the beaches and source of beach sediments.

A number of papers have been written about certain specific areas in the bay. Nicholson, Grant, Shepard, and Crowell (1946) made a detailed study of the marine geology and oceanography for a proposed yacht harbor at Malibu. Articles written about Santa Monica beaches include: Anonymous (1917, 1933); Emery (1954b, 1955); Handin (1949); Handin and Ludwick (1949); Lapsley (1937); Larsen (1939, 1942); Schupp (1953); and Shepard (1935, 1938).

These papers concern beach erosion, littoral drift, the effects of the construction of the breakwater at Santa Monica, and information regarding the gravel beaches that occur along the Malibu-Santa Monica shoreline.

A. G. Johnson (1935, 1940a, 1940b, 1940c, 1951) was interested in the erosion along the Venice shoreline and made a special effort to obtain records of changes along the shore. His reports and data have been of great use in studying the nearshore zone. Anonymous (1916) and Leeds (1916) also wrote short reports on the Venice beaches.

The proposal for a harbor in the Playa del Rey and Ballona Creek area has resulted in much information for that region. The U. S. Army, Corps of Engineers, Beach Erosion Board (1938, 1948c, 1948d, 1948e) has made a detailed study of the region, and the U. S. Waterways Experiment Station, Vicksburg, Mississippi (1935, 1936) has conducted model studies of the Ballona Creek region. The Los Angeles Regional Planning Commission (1938, 1940), Los Angeles Department of City Planning (1941), and Stapleton (1952) have written reports on the planning of the harbor, beach development, and recreation in the Santa Monica - Venice district. Olsson-Seffer (1905, 1910a, 1910b), Purer (1936), Merriam (1949), and Pierce and Poole (1938) have studied the sand dunes along the Playa del Rey, Venice, and El Segundo region. Marshall (1934) gave a description of the beaches at Manhattan Beach.

The Beach Erosion Board (1948b, 1950a, 1950b, and other unpublished reports), Congressional Documents (1949-50b), and Marlette (1954) have studied the Redondo Beach region, especially in regard to the extension of the breakwater.

Additional reports that are applicable to the beaches of Santa Monica Bay include: Beach Erosion Board (1950a, 1950b), which studied the beaches between Point Mugu and the San Pedro breakwater; California Bureau of Sanitary Engineering (1943) on the pollution of the Santa Monica Bay beaches; Grant (1946), and Emery and Foster (1948) on water tables in beaches; and the Beach Erosion Board (1948a), and Grant (1943) discussed littoral drift.

A number of articles have been written about beach development and shore line changes including: Chace (1953), Drury (1936), Grant (1938), Grant and Shepard (1937, 1938a, 1938b, 1946, 1949), and Griffin (1940).

Land Geology

Among the very large number of reports which deal with the geology of the land adjacent to Santa Monica Bay are the following: Bailey (1943); Woodring, Bramlette, and Kleinpell (1936); Woodring, Bramlette, and Kew (1946); and Woodring and Kew (1932), who have studied Palos Verdes Hills. Hoots (1931); Baily and Jahns (1954); Durrell (1954); Kelley (1932); Peline (1952); Place (1952); Robertson (1932); and Soper (1938) have studied the geology of Santa Monica Mountains. Vickery (1927a, 1927b) has studied the physiography of the Los Angeles coastal belt, while Bailey (1943); Cotton (1942, 1944); Davis (1931, 1932); Davis, Putnam, and Richards (1930); Goldberg (1940); Livingston (1939); Place (1952); and Wheeler (1936) were concerned primarily with the uplifted marine terraces and physiography of the Santa Monica Mountains region. Driver (1949) gave a summary on the origin

and evolution of the Los Angeles Basin. Poland, Garrett, and Sinnott (1948); Poland, Piper, and others (1945) studied the coastal region, especially in regard to ground water. Reed (1951) and Reed and Hollister's (1951) book on the geology of California is an excellent source of information for additional information on the geology of southern California; and the recent publication by the California Division of Mines, (Bulletin 170) of the geology of southern California gives the very latest information for this region.

GEOLOGIC AND GEOGRAPHIC SETTING OF SANTA MONICA BAY

Introduction

The Los Angeles Basin is bounded by the Santa Monica Mountains and the San Gabriel Mountains on the north; the Pacific Ocean and Palos Verdes Hills on the west and south; and partly by the Santa Ana Mountains and Puente Hills on the east. The San Pedro and Santa Monica Shelves are seaward extensions of the Los Angeles Plain. Most of the regional faulting trends northwest-southeast, and numerous parallel or en échelon faults have resulted in the topographic prominences; varying from mountains along the eastern border to hills and knolls in the Los Angeles Plain area. The mountain ranges along the northern border of the Basin are controlled by east-west trending faults.

Essentially all of the present major topographic features in the coastal region, and probably much of the relief inland, were formed by deformational earth movements during Middle and

Late Pleistocene time. The hills and knolls in the Los Angeles Plain area, the stream cuts, marine terraces and high sea cliffs, and the great submarine canyons were probably formed at this time. In addition, thick deposits of marine and continental sediments were deposited over large parts of the region during and subsequent to the Pleistocene.

Woodford, et al., (1954) have given an excellent summary of the geological history of the Los Angeles Basin and a resume of their report is given as follows:

"The Los Angeles Basin during Pliocene time was a marine embayment somewhat larger than the present lowland area. Its southwestern margin during most of this time probably was a shelf, which though submerged, was thousands of feet higher than the central part of the basin. The basin during Miocene time was still larger, extending inland as far as Pasadena and Pomona and merged into the Ventura Basin to the northwest. . . During Middle Miocene time the basin was bounded on the southwest by a land mass (Catalina) that apparently was composed exclusively of glaucophane schist and related rocks. Today the basin's central floor is buried beneath at least 20,000 feet of Miocene and later sedimentary rocks. The southwestern shelf has a crystalline schist floor . . . that is 1,000 feet above sea level in the Palos Verdes Hills, mostly 4,000 to 10,000 feet below sea level north of those hills, and as much as 14,000 feet subsea beneath Long Beach. A similar shelf on the northern and eastern sides of the basin is floored by pre-Upper Cretaceous crystalline rocks. . . at depths that probably range from about 15,000 feet subsea to approximately sea level. The Los Angeles Basin is somewhat similar in its geologic history to the Ventura Basin. Each was a deep marine trough at the beginning of Pliocene time, and each was then filled. . . with sediments containing fossils characteristic of shallower and shallower water, until the uppermost, largely continental, Pleistocene strata were deposited."

Land Forms

Santa Monica Bay is a crescent-shaped indenture of the southern California coast with three major land provinces forming its boundaries (Fig. 1). These physiographic provinces are the Santa Monica Mountains to the north, the Los Angeles

Figure 1. Major land provinces adjacent to Santa Monica Bay.

LANDFORM BOUNDARIES ADJACENT TO SANTA MONICA BAY

—— Mountains and other major land divisions
 - - - - - Smaller features

a - Simi Hills	k - Baldwin Hills
b - Verdugo Hills	l - Rosencrans Hills
c - San Rafael Hills	m - Ocean Park Plain
d - Repetto Hills	n - Ballona Creek Gap
e - Elysian Hills	o - El Segundo Sand Hills
f - Santa Monica Plain	p - Torrance Plain
g - Hollywood Plain	q - Dominguez Hill
h - Sawtelle Plain	r - Dominguez Gap
i - La Brea Plain	s - Signal Hill Uplift
j - Downey Plain	t - Long Beach Plain

SUBDIVISIONS OF THE LOS ANGELES COASTAL PLAIN
 MODIFIED AFTER POLAND ET AL 1945 & MCGILL 1954

Coastal Plain to the east, and the Palos Verdes Hills to the south. That part of the Los Angeles Coastal Plain nearest to shore can be further sub-divided into the Santa Monica Plain, Ocean Park Plain, Ballona Creek Gap, and the El Segundo Sand Hills (Poland, et al., 1945; and McGill, 1954). Because the topography, drainage, structure, and rock composition in the provinces and sub-provinces have played an important role in the submarine geologic history of the adjacent continental shelves and borderland, each area is briefly described.

Santa Monica Mountains

The Santa Monica Mountains vary in elevation from 1,200 feet in the east to more than 3,000 feet at their western end. The rocks in the mountains range in age from Mesozoic to Recent and the sedimentary sequences total more than 26,000 feet in thickness. Many varieties of rock occur including slate, schist, quartz diorite, basalt and andesite flows, tuffs, breccias, basaltic breccia, rhyolite, trachyte, sandstones, shales, and conglomerates (Hoots, 1931; Durrell, 1954; and Bailey, 1954).

The complex structure of the Santa Monica Mountains is shown on geological maps by Durrell (1954) and Bailey (1954). The major faults in the Santa Monica Mountains along the northern part of Santa Monica Bay are shown in Figure 2. The Malibu fault trends east-west along the base of the mountains close to the shore line, and crosses the coast west of Point Dume and Las Flores Canyon. From available data (Bailey, 1954, and Hill, 1954) it is believed that the Santa Monica Mountains

Figure 2. Major faults in Santa Monica Mountains along the northern boundary of Santa Monica Bay.

DISTRIBUTION OF FAULTS
IN SANTA MONICA MOUNTAINS

have been uplifted and shifted to the west in relation to Santa Monica Bay. Most of the other faults within the mountains are small and probably have had little effect on the geological history of the bay.

Except in the vicinity of Malibu Creek, the slopes of the Santa Monica Mountains adjacent to the bay are steep and in places form nearly vertical sea cliffs. The coast is irregular, being cut by numerous canyons, and is quite rocky; especially between Las Flores Canyon and Santa Monica Canyon. The beaches from Malibu to about Las Flores Canyon are sandy and continuous, but east of this point to about Santa Monica Canyon the natural beaches are small. The earliest topographic sheets of the U. S. Coast and Geodetic Survey, made in 1876-77, show narrow sandy beaches extending from Point Dume to Las Flores Canyon. From the latter point to Castle Rock the shore was mostly rocky. The construction of the Coast Highway and the use of groins has slightly altered the shore, but the beaches are probably about the same as they were when the first surveys were made. From Castle Rock to Sunset Boulevard, the old maps show a beach about 75 feet wide, but from here southeast the shore was rocky for a short distance. From this rocky shore to Santa Monica there was a continuous sandy beach. Man has altered this part of the shore appreciably in the last 50 to 80 years. From Potrero Canyon to Santa Monica Pier the shore is bordered by a nearly vertical sea cliff which varies in elevation from 60 to 160 feet above sea level.

Santa Monica Plain

Hoots (1931, p. 130) designated the south flank of the Santa Monica Mountains as the Santa Monica Plain. Poland, et al. (1945), on the other hand, restricted the name to the older alluvial surface lying west of Beverly Hills. The underlying platform was cut by marine erosion in Late Pleistocene time and subsequently was covered partially by marine and continental sands and gravels. While the plain and most of its deposits are considered to be of Late Pleistocene age, the surface has been modified in Recent time by erosion as shown by the broad channels and gullies. Later deposition of coarse deposits has partially filled the channels.

Ocean Park Plain

The Ocean Park Plain is part of the Santa Monica Plain as designated by Hoots, but was restricted by Poland, et al. (1945) to the region "whose surfaces is composed substantially of marine deposits of Late Pleistocene (Palos Verdes) age, and which lies largely in the south-west angle of Pico Blvd. and Bundy Drive." This mesa extends inland from the coast about 3 miles, is 1-2 miles wide, varies in height from about 125 to 200 feet, and is relatively undeformed. The plain has been divided into three smaller units by Poland: (1) a small bench to the east, about 190 feet above sea level, (2) an extensive central plain which slopes gently southward, and (3) a ridge-and-trench area paralleling the coast, considered to be Upper Pleistocene in age (Hoots, 1931). According to Hoots, part of the western region consists of old sand bars

and shoreline bluffs formed at a higher stand of sea level. The material composing these old sand bars is a fine brown thin-bedded sand that has been washed free of all clay material.

Ballona Gap

Ballona Gap is a terrestrial feature of importance in the study of Santa Monica Bay as large amounts of sediment have been carried through it to the shelf and offshore region. Drainage through the gap has probably played an important role in the history of Santa Monica submarine canyon and perhaps, to a minor extent, Redondo Canyon. Ballona Gap at its narrowest place is 1.2 miles wide where it cuts through the Inglewood-Newport fault zone, and is about 10 miles long in its present extent from the coast to the east end of Baldwin Hills. Bluffs up to 400 feet high were cut by the old stream as it flowed between Baldwin Hills and Beverly Hills. There is evidence that an antecedent stream existed on the surface of Late Pleistocene (Palos Verdes) age before it was deformed. The stream had sufficient eroding power to cut across the warped rocks as quickly as they were uplifted.

The ancestral Los Angeles River which formed the Ballona Gap cut a channel at least 50 feet below sea level at Ballona Creek outlet, and 400 feet deep where it crossed Baldwin Hills. Subsequent deposition of gravels and sands has filled the channel at the coast and to a depth of 80 feet northeast of Baldwin Hills (9 miles upstream). According to Poland, et al., (1948, p. 51), the incised stream graded to base level substantially

more than 50 feet below present sea level and possibly extended as much as two to three miles seaward from the present shoreline, presumably toward Santa Monica Canyon. According to Layne (1935), the Los Angeles River was flowing through Ballona Gap in 1815 and continued until 1825 (Kenyon, 1951) when a particularly severe flood diverted the river to the south where it joined the San Gabriel River emptying into San Pedro Bay. Other extensive floods in 1862 and 1884 caused part of the waters to return temporarily to Ballona Creek, but since 1884 the Los Angeles River has discharged only into San Pedro Bay (Troxell and others, 1942).

The mouth of the stream apparently migrated north and south of the Ballona Creek outlet, for the earliest U. S. Coast and Geodetic topographic maps show the natural outlet discharging at the end of a long sand spit, while landward of the split there was a salt marsh averaging about one mile in width. In 1906 and 1908 the outlet was "fixed", but in 1936 it was again moved 1,400 feet farther to the north.

At the present time Ballona Creek has a drainage area of approximately 131 square miles from the southern slopes of the Santa Monica Mountains and parts of Baldwin Hills (Fig. 3). Since the construction of flood control channels and other works by man, little detrital material is brought to the bay through this course.

Probably the most important rifting in the Los Angeles Basin is the Inglewood-Newport fault zone, which occurs in the vicinity of Ballona Creek. Three faults which run perpendicular to the old channel are associated with this

Figure 3. Drainage areas tributary to Santa Monica Bay.

fracture zone and are known in the vicinity of Ballona Creek. From east to west they are: the Inglewood, Overland, and Charnock faults. The latter two have only been identified below the land surface, largely on the characteristics of the ground water table. In each case, the western side of the rift has been uplifted relative to the eastern block. Poland, et al., (1948) points out that the transverse profiles across Ballona Creek show that the gravels and sands within the old stream channel dip to the south and frequently are more than 40 feet thicker on the southern side of the channel. This could indicate that a fault partly controls the stream channel, and may also account for the relatively steep and straight bluffs along the Ballona Creek escarpment. The circulation of ground water does not indicate one way or the other whether an east-west fault exists. However, as an alternative to faulting, it is suggested that the stream migrated to the south and as a consequence cut a deeper channel in this direction.

El Segundo Sand Hills

From the Ballona Creek outlet to Malaga Cove, a distance of 11.7 miles, there are extensive coastal sand dunes which have been termed the El Segundo Sand Hills (Poland, et al., 1945). Merriam (1949) made a comprehensive study of the structure, composition, and geologic history of the sand dunes. She notes that the main part of the sand dunes ranges from 2.0 miles to 4.2 miles in width, while the active dunes, which lie atop the main ridge, have an average width of 0.4 mile

between Playa del Rey and Redondo Beach. The dunes range in elevation from 85 to 185 feet above sea level, and have an estimated volume of 36 billion cubic yards of sand. Vegetation has anchored the dunes in many places so that today running water and wind cause only minor changes in their structure.

Lithologically, the cemented dune sands compare closely with the beach sands now found in Santa Monica Bay. Subrounded sand grains were found to be very abundant in only the larger sand sizes and frosting and pitting, generally believed to result from wind action, occur on about 5 to 15% of the grains. The coarse sands appear to be derived primarily from a granitic source. Reddish-brown sands, similar to the red sands found offshore, are common in the sand dunes; the color resulting from the presence of iron oxide as a stain on the grains. According to Poland, et al. (1945), Woodring, et al. (1946), and Merriam (1949), a marine platform, correlated with the lowest and youngest terrace in Palos Verdes Hills has been deformed along the Newport-Inglewood fault zone as have the sands of Upper Pleistocene age which were deposited on its surface during a higher stand of the sea. After the deposition of this sand (Palos Verdes formation), a large region west of the Newport-Inglewood fault zone was uplifted above sea level. Nonmarine terrace material of Upper Pleistocene age was deposited on this uplifted surface in the Palos Verdes Hills and various places inland. There is some dispute as to whether the El Segundo Sand Hills are partly offshore bars (Eckis, 1934; Poland, et al., 1948) or wholly of eolian origin (Merriam, 1949). Merriam concluded that the sand hills are

composed entirely of eolian sands lying directly on the Palos Verdes sand in most of the area, and that the sand dunes were formed continuously as the sea regressed across the Palos Verdes surface.

Zielbauer and Davis (undated) note that the Palos Verdes formation in the Hermosa-Manhattan Beach region is composed mainly of sands and gravels which are similar to the overlying coastal deposits, except that they occur somewhat farther inland and include calcitic fragments. The formation is absent in some of the region and its absence is attributed to marine and/or fluvial activity. There is more or less continuous horizon of relatively impervious deposits composed of silts, silty sand stringers, sandy clays, and clays that lie directly below the sand dune and coastal deposits. This layer, called the "clay cap", is unusually flat, varying from 10 feet above sea level to about 10 feet below sea level, and reflects the underlying structure which consists of transverse drainage channels. The clay cap feathers out completely at the present strand line, and it is absent in a well 800 feet inland.

The drainage of the El Segundo Sand Hills (Fig. 3) shows that only a narrow belt of that shoreline adjacent to Santa Monica Bay drains into the bay.

Palos Verdes Hills

The Palos Verdes Hills, which form the southern and southeastern boundary of Santa Monica Bay, are a conspicuous uplift along the southern border of the Los Angeles Basin. For the most part, the hills have a relatively simple structure consisting of broad gentle folds which form an anticlinal structure.

There are few major faults, but those that do occur roughly parallel the axis of the hills. The most important fault is not exposed at the surface, but is a major structural feature in the schist basement and the immediately overlying rocks. This fault has been called the "San Pedro Fault" by subsurface geologists, but Woodford, et al. (1954) have termed it the "Palos Verdes Fault Zone". According to Woodring et al. (1946) the Palos Verdes Hills were uplifted with the San Pedro fault (or the Palos Verdes fault zone) separating the hills from the Los Angeles Basin. This structural feature conceivably extends far out into Santa Monica Bay (Fig. 4).

The exact age of the major faulting along the northern border of Palos Verdes Hills is still unknown, but the zone is probably still active. The strongest deformation in the Palos Verdes Hills took place during the Upper Pliocene. Less marked deformation during the Middle Pleistocene, and still weaker movements occurred near the close of the Pleistocene period. Deformation has been so recent along the northern border of Palos Verdes Hills that the lower marine terrace and its associated deposits have been slightly to moderately deformed.

The basement rock is glaucophane schist and altered basic igneous rocks of probable Jurassic age. Unconformably above the basement rocks are several thousand feet of strata of Miocene and Pliocene age and a relatively thin veneer of terrace deposits of Pleistocene age. The rocks of Miocene age are cherty, phosphatic, and silty shales, mudstones, basaltic sills and tuffaceous beds. Pliocene rocks include

Figure 4. Block diagram of Palos Verdes Hills and adjacent areas.

bluish gray glauconitic and foraminiferal siltstones. Deposits of Lower Pleistocene age are marine marls, silts, and sand, while sediments of Upper Pleistocene age are mainly nonmarine deposits.

The shores around Palos Verdes Hills are rocky with steep sea cliffs. The beach sediments are mostly cobbles and only occasionally are there any small sandy pocket beaches.

SUBMARINE TOPOGRAPHY OF SANTA MONICA BAY

The bathymetry of Santa Monica Bay has been determined largely from U. S. Coast and Geodetic Survey "smooth sheets" numbers 4559, 4784, 5235, 5364, 5390, 5396, 5397, 5507, 5653, 5851, and 6259. Certain unavoidable errors were introduced when contouring due to survey methods employed by the U. S. Coast and Geodetic Survey. For example, most of the sounding lines, especially those close to shore, were run along lines parallel to shore. As a result, the exact position of the constructed contours are not as accurately positioned as they would have been if the sounding lines had been run normal to the coast. Also, soundings were rounded off to the nearest fathom, and the conversion to feet introduced more uncertainties as to the exact position of the contours. None of the inaccuracies mentioned are critical and they become less important with increasing depth. Additional soundings by the VELERO IV were used only in the vicinity of the terminal ends of the proposed outfalls and in the rocky area to the south of Santa Monica Canyon. The data gathered by the VELERO IV indicated no significant changes of the nearshore topography so that

U. S. Coast and Geodetic Survey soundings were used almost exclusively in that area.

Submarine Physiographic Provinces

The general physiographic divisions of Santa Monica Bay are: (1) the Shelf, (2) Redondo and Santa Monica submarine canyons, (3) the Basin Slope, and (4) Santa Monica Basin.

Shelf

For convenience in describing the submarine topography and other portions of this report, that part of the shelf that lies between the two submarine canyons is designated the "outer shelf", or "central shelf projection". The Santa Monica Shelf extends to a depth of approximately 270 feet. At this depth a pronounced steepening of the sea floor indicates the shelf break. The width varies from a few hundred feet at the head of Redondo Canyon to more than 8 miles between the two submarine canyons. North of Santa Monica Canyon the shelf is very constant in width and the edge follows the shape of the present coastline. From Figures 5, 6a, & 6b, it can be seen that the bottom slopes seaward evenly and has a gradient of about $\frac{1}{2}$ degree.

Nearshore, where sandy beaches are present, one or more parallel troughs and ridges are often present. These long-shore troughs and bars are generally transitory, moving up and down in the nearshore zone and their presence, absence, and position depend upon currents, storms, the tide, and wave height. The shifting of sand, and even gravel along the bottom

Figure 5. Submarine topography of Santa Monica Bay.

118° 30'

40'

34'

50'

50'

40'

SANTA MONICA BAY

CONTOUR INTERVALS

10 FT. INTERVAL: 0-300 FT.
100 FT. INTERVAL: 300-600 FT.
300 FT. INTERVAL: 600-2700 FT.

SANTA MONICA

PACIFIC PALISADES

MALIBU POINT

SANTA MONICA

VENICE

BALDWIN CREEK

PLAYA DEL REY

EL SEGUNDO

MANHATTAN BEACH

HERMOSA BEACH

REDONDO BEACH

LOS VERDES PT.

SANTA MONICA SANDWICH

SANTA MONICA BASIN

Figure 6. Fathometer traces of Santa Monica Shelf.

- (a) Location of fathometer traces.
- (b) Representative fathograms.

may cause pronounced but local relief within the nearshore zone (Schupp, 1953). The shifting of bottom material in the form of longshore troughs and bars is generally confined to water less than about 15 to 20 feet deep (Shepard, 1950).

With the exception of the surf and nearshore zone, most of the shelf is devoid of any significant relief. Small current and wave formed ripples, marks, and burrows caused by bottom dwelling animals may form mounds, depressions or undulations a few feet high. However, these features like the bars and troughs generally are not permanent.

A large number of shallow-water fathograms to 300 feet were taken by the VELERO IV over the central part of the Santa Monica shelf. It was observed that much of the shelf had virtually no relief while other parts had significant changes in elevation. Generally, the surface of any continental shelf has small features consisting of mounds, ridges, depressions, or undulations called micro-relief. Features about three feet high are usually the smallest that can be determined by an echo-sounder due to the motion of the ship caused by sea and swell. Ripple marks and mounds formed by organisms are, therefore, too small to be recorded. A special study of the shallow-water fathograms collected in Santa Monica Bay was made in order to find the extent, type, and distribution of micro-relief on the shelf (Staff, Allan Hancock Foundation, 1956). Figure 7 shows the tracklines along which the fathograms were obtained and studied, and Figure 8 shows the different types and distribution of micro-relief which were then plotted along the trackline. After all fathograms were examined and plotted,

Figure 7. Shallow water fathometer tracklines on Santa Monica Shelf.

VELERO IV SHALLOW-
WATER FATHOMETER
TRACKLINES ON
SANTA MONICA
SHELF

300 FT. CONTOUR

33°
55'

33°
50'

118° 30'

118° 30'

35'

35'

33°
55'

33°
50'

Figure 8. Micro-relief of Santa Monica Shelf.

MICRO-RELIEF OF SANTA MONICA SHELF

AREAS ESSENTIALLY SMOOTH AND FLAT - MOUNDS OR OTHER SMALL TOPOGRAPHIC HIGHS ARE VERY RARE.

TOPOGRAPHY VARIABLE - DISCONTINUOUS AREAS OF SMOOTH TOPOGRAPHY, SMALL MOUNDS (3-10 FEET HIGH) & UNDULATIONS FAIRLY COMMON.

TOPOGRAPHY VERY ROUGH - SHARP PEAKS & RIDGES PROJECT ABOVE IRREGULAR BOTTOM. RELIEF FREQUENTLY 10 TO 40 FEET.

--- 300 FT. CONTOUR

three types of micro-relief were outlined: smooth, variable, and irregular.

A wide belt of smooth topography extends from nearshore to varying distances out on the shelf (Fig. 8). The only distinguishable irregularities within this area are isolated mounds a few feet high. Depressions are conspicuously absent within the zone. Near the edge of the shelf, occasional well-defined terraces or flat areas can be seen on the fathograms, some of which can be seen on the topographic map of the bay (Fig. 5), but little micro-relief is evident. An especially well-defined terrace is present at the boundary between the smooth and irregular zones and extends a short distance north towards Santa Monica Canyon.

The zone of variable topography is generally seaward of the smooth areas. The offshore limit could not be determined accurately because of the transitory nature of the boundary and the lack of fathograms in this region. Within this zone are broad areas of no micro-relief and smaller sections having low mounds, undulations, and small steps or terraces. Also included in this zone is the sudden steepening at the shelf break and the irregular topography associated with the submarine canyons. Along the edge of the shelf and the upper part of the basin slope, are numerous notches, steps, and small terraces. Closer to shore, north of Santa Monica Canyon, are several gullies 20 to 30 feet deep which are, perhaps, similar to those described by Buffington (1951), and Emery and Terry (1956). Although there are many mounds and irregularities within this general area, none compare in

size and number with those in relatively rugged topography of the irregular zone.

The irregular zone consists mainly of mounds and ridges which project 10 to 40 feet and occasionally 60 to 80 feet above the sea floor. The flanks of many of these mounds and ridges appear jagged, irregular, and steep on fathograms. The slopes may be locally more than 15° , but generally are less than 10° or 20° . Some of the mounds are connected by low ridges and these also have irregular and jagged sloping sides. Individual mounds are 2,000 to 3,000 feet in diameter; some are smaller or larger, but this appears to be the average size. The area enclosed by the irregular zone is known to have much gravel and some bedrock so that the relief evidently is due to rock outcrops and patches of gravel. Because the micro-relief chart is based only on fathometer traces and not on bottom sampling, and because the fathometer does not necessarily distinguish between bottom types, the limits of the rock and gravel area differ slightly on the two charts (Figs. 8 and 13).

Redondo and Santa Monica Canyons

The head of Redondo Canyon consists of an amphitheater-like bowl which is located a short distance from the shore. The canyon has a relatively flat floor throughout most of its length, has only a few bends, and has a wide terminal end at a depth of approximately 2,200 feet. According to Shepard and Emery (1941, p. 64, pl. 12), the gradient of Redondo Canyon decreases along its course; being 8% at the head, 2.5% at the

outer edge, and averaging 4.1%. The axis of the terminal end, like Santa Monica Canyon, swings to the south and appears to terminate in a fan or delta (Fig. 9). The south wall of the canyon generally is much steeper than the north side and has local gradients of 25%. Two large tributaries are located on the north flank of Redondo Canyon, whereas only small ones are found on the south side. Shepard and Emery (1941, p.64) compared soundings within the large tributary closest to shore on the north side of the canyon. They found evidence that recent soundings are consistently deeper than the soundings taken about 50 years before which suggests slumping. Figure 9 shows cross-sections of Redondo Canyon taken at regular intervals from near its head beyond its terminal end.

Santa Monica Canyon starts at a depth of approximately 180 feet about $3\frac{1}{2}$ miles offshore. Unlike Redondo Canyon, it has a sinuous course, starting in a northeast-southwest direction, turning slightly northwest, and then south at the outer end. Santa Monica Canyon also differs from Redondo in that it appears to be less rugged and complex, is more asymmetrical, and has only small and few tributaries. The average gradient along the axis of the canyon is 3%. Figure 6 shows fathograms taken across the upper part of the canyon. It will be noted that the canyon has a "V" shaped cross-section at the bottom but the north side flattens out forming the wide north side of the canyon and part of the basin slope. A few terraces along the side of the canyon are also conspicuous.

Figure 9. Profiles of Redondo Canyon.

Basin Slope

Off most coasts the continents are surrounded by a continental shelf and continental slope. The continental slope forms the seaward margin of the continents from which the water depth increases to the abyssal sea-floor several thousand feet deep. Off southern California, however, the continent is separated from the abyssal sea by a series of basins and ridges. The slopes bordering these basins are called "basin slopes" to distinguish them from true continental slopes.

The basin slope in Santa Monica Bay is that part of the sea floor seaward of the shelf and terminates on the floor of the Santa Monica Basin. The average gradient is 5° seaward of the outer shelf. The slope is broken into several segments as a result of the two submarine canyons. West of the outer shelf and south of Palos Verdes Hills, it is well-defined, but south of Malibu and on the north side of Redondo Canyon the basin slopes are partly the sides of submarine canyons. Fathograms along the slope indicate a generally smooth surface broken occasionally by small terraces or steps. Profiles taken south of Malibu indicate that channels, locally to 60 feet in depth are present.

Santa Monica Basin

A small part of the Santa Monica Basin can be seen in the lower left corner of Fig. 5. The floor of the basin is relatively flat but deepens slightly to the west. Shepard and Emery (1941, p. 64) believe that there is evidence of a

submerged fan off the terminal end of Redondo Canyon, and the profiles shown in Figure 9 confirm that a fan is present. However, there are not enough soundings off Santa Monica Canyon to determine the nature of its terminal end.

APPARATUS AND METHODS

Prior to collecting bottom samples in Santa Monica Bay, U. S. Coast and Geodetic Survey "smooth sheets" and Shepard and MacDonald's (1938) report were closely examined. Areas where rock and gravel had previously been reported were examined by rock dredges (Fig. 10-E) and in areas where the type of bottom material was unknown or in doubt, an underway sampler (Fig. 10-C) was used. Additional information regarding the bottom character was obtained by the use of a shallow-water recording fathometer, when it was found that extensive patches of rock and sometimes gravel areas could be observed on fathograms. After the general locations of rock, gravel, and the finer sediments had been delineated, a snapper sampler (Fig. 10-D) or an Hayward grab sampler (Fig. 10-A) were used for the collection of larger unwashed samples. In areas where the vertical distribution of sediments was of importance, cores (Fig. 10-B), jettings, and samples by divers were obtained. Samples obtained by divers were limited to water less than 150 feet.

A preliminary determination of bedrock was accomplished mainly on the basis of the "feel" of the cable as the dredge was slowly towed across the bottom. Further criteria used in recognizing bedrock included the freshly fractured aspect

Figure 10. Bottom sampling equipment used aboard the
VELERO IV.

of the rock, and if more than one fragment was obtained, the similarity in lithology. Gravel and rock not in place, i.e., that had been transported, generally were determined on the basis of dissimilar lithology, rounded nature of the fragments, and the lack of fresh fractures. The dredge generally was towed slowly from a region where no rock and/or gravel existed towards regions where bedrock or gravel was believed to be present. At the first indication of striking hard bottom the ship was stopped and the dredge brought aboard. By repeatedly lowering the dredge and approaching the rocky and gravelly areas from different directions, the general boundaries of these areas were determined. Representative samples of bedrock and gravel were brought back to the laboratory for later study.

Most snapper samples were obtained in conjunction with hydrographic work so that a grid pattern was not used in collecting bottom sediment. However, towards the end of the survey a number of samples were collected from sparsely sampled areas. Material gathered by a snapper or the Hayward grab were briefly described and placed in air-tight glass jars for later physical and chemical studies in the laboratory.

Cores of bay sediment were split, briefly described noting especially changes in texture, and placed in jars and brought back to the laboratory for studies similar to surface samples. Some problems associated with use of gravity coring instruments have been discussed by Emery and Dietz (1941). Their discussion of true core lengths versus collected core length is worth notice.

A gravity core sample is representative of all depths penetrated, but the in situ depth of a given layer may be as much as twice its actual depth in the core. The difference between recovered core length and the depth of penetration is produced by the thinning of sediments at the cutting edge of the core barrel. Thus, the depths of penetration given for gravity core samples in this report may be up to two times the length of the core recovered. However, since most of the sediment was of sand, or non-uniform sediment, the core length was usually almost equal to the depth of penetration. Since it is virtually impossible to calculate the depth of penetration because of the heterogeneity of most shelf sediment, the outside of the core barrel was greased to determine the depth of penetration.

Figure 11 shows the location and apparatus used to collect the bottom samples in Santa Monica Bay.

Laboratory Studies

Mechanical Analysis

In a typical sediment analysis, twenty-five to fifty grams of sediment are washed through a 250 mesh screen with .061 mm square openings to separate silt and clay (grain diameter less than .062 mm) from sand and gravel (grain diameters greater than .062 mm). The coarse fraction is dried and weighed. Gravel (grain diameters greater than 2 mm) is separated from the coarse fraction by screening, and weighed to determine its proportion in the entire sediment. Grain-size distribution of the sand portion of the coarse fraction

Figure 11. Location of sediment samples.

SANTA MONICA BAY BOTTOM SAMPLES

300 FT. BOTTOM CONTOUR

- HAYWARD GRAB STA.
- SNAPPER STA.
- ▲ UNDERWAY STA.
- CORE STA.
- DREDGE STA.

(grain diameters between 2 and .062 mm) is determined using the sedimentation method described by Emery (1938). Grain-size distribution of the silt and clay is determined by the standard pipette method (Krumbein and Pettijohn, 1938, p. 165-170). The total weight of silt and clay is determined from the pipette analysis. From these data the per cent of gravel, sand, silt, and clay are determined and a cumulative curve of the grain-size distribution is drawn from which the median diameter and Trask's sorting coefficient were determined.

Calcium Carbonate

In a sediment calcium carbonate is considered to be the material soluble in cold, dilute hydrochloric acid. This value is determined by slowly adding the acid to a dried and weighed sample until effervescence ceases. After this the remaining sediment is washed with distilled water and any remaining acid decanted off. The remaining sediment is dried and weighed to determine the per cent calcium carbonate (dry weight) for the entire sample.

Organic Carbon

Organic carbon content can be determined by the Allison (1935) method of oxidizing a 500 mg sample of sediment with chromic acid and the excess chromic acid back-titrated with 0.2 N ferrous ammonium sulfate. Under the conditions of the determination, free carbon is not oxidized and carbonates, being already oxidized, are not affected. Although this method is rapid, convenient, and duplications check within one per cent, it is not an absolute method because it assumes

that all organic matter is in the same state of oxidation. In addition, any ferrous ions present will also be oxidized, resulting in slightly higher values.

Mineralogy

The percentages of heavy minerals in the sand fraction are determined by heavy liquid separation using acetylene tetrabromide ($C_2H_2Br_4$, specific gravity 2.96 at 20°C). Minerals having a density greater than the liquid sink while those lighter than the liquid float. Thus, two different groups of minerals - the "heavies" and "lights" - are separated and the per cent of heavy minerals calculated. The heavy minerals are then identified by standard petrographic methods. The light minerals can be stained and identified using procedures outlined by Twenhofel and Tyler (1941, p. 131). Determination of mineral percentages in individual samples is based upon counts of approximately 200 grains.

The sand fraction (1/16 mm to 2 mm diameter) of each sample is also usually examined with a binocular microscope to establish sand types and to outline mineral associations within various environments.

Sphericity and Roundness

Sphericity and roundness are two attributes of particle shape. Roundness refers to the sharpness of the corners and edges of a grain, whereas sphericity is a measure of the shape of a grain as related to a sphere. The sphericity and roundness of sand grains are usually determined by visual comparison of the grains with charts prepared by Rittenhous (1943) and Krumbein (1941).

Rock and Gravel

Hand lens identifications of rock types are made on all gravel and bedrock samples from the sea floor. During the identification of each sample, the roundness and sphericity, nature of fracturing if present, and the presence or absence of borings and encrusting organisms on the individual pieces of rock are noted as an aid in determining whether they represent a fragment of bedrock or rock in place.

BOTTOM MATERIALS

Unconsolidated Sediments

The distribution of the unconsolidated sediments of Santa Monica Bay is based on the examination of 364 samples, and to a minor extent on the notations of the U. S. Coast and Geodetic Survey. The sediments are classified using a three component system based upon gravel, sand, and silt percentages, as shown in Figure 12. Because of the low volume of clay in the shelf sediments, it is possible to include that fraction with the silt and still retain the three component system. The boundaries for the per cent gravel, sand, and silt fractions in Figure 12 have been modified so that minor components could not aggregate more than 20% of the sample. A sample containing 85% sand, 9% gravel, and 6% silt is classified as a sand. If it contains 76% sand, 17% gravel, and 9% silt it is a gravelly sand. A sample containing 70% silt, 15% gravel, and 15% sand is a sandy gravelly silt. Sands were further subdivided on the basis of color into two sediment sub-types.

Figure 12. Detrital sediment diagram.

Areal Distribution of Sediment Types

The least common sand sediment sub-type in Santa Monica Bay is red sand (Fig. 13). This sediment is characterized by an iron oxide staining of all organic (shells) and detrital constituents. Red sand occurs in three small patches near Hyperion, and in a narrow band off Palos Verdes Hills. The sand at the latter location is coarse and contains abundant shell fragments, whereas adjacent to Hyperion it is finer and shell detritus are absent or rare. Similar sands have been reported from many other locations off this coast and Baja California, including: San Pedro Shelf (Moore, 1951), San Diego (Emery, Butcher, Gould, and Shepard, 1952), near San Nicolas Island (Norris, 1951), in Todos Santos Bay (Uchupi, 1956), San Francisco (Bache, 1852, 1856; Alden, 1956), and south of Palos Verdes Hills in the vicinity of the Orange County, and Whites Point outfalls during the present survey. Additional data on the characteristics of the red sand will be found in the section on "Coarse Fractions".

Olive green sand occurs in three small patches in the southern part of the bay near Redondo Canyon; in a small area near the Ballona Creek Outlet; and to a larger extent at the head of Santa Monica Canyon. The sand at the head of Santa Monica Canyon is distinguished from the other olive green sand by the abundance of rock fragments, which are rare or absent in the other areas. The greatest areal distribution of olive green sand is in a zone extending from Palos Verdes Hills to Malibu. This deposit is widest near Hyperion and narrows to the south and north. The large deposit near shore

Figure 13. Bottom materials of Santa Monica Bay.

SANTA MONICA BAY

BOTTOM MATERIAL

300 FT. BOTTOM CONTOUR

ROCK

GRAVEL

SANDY SILTY GRAVEL

RED SAND

OLIVE GREEN SAND

SILTY SAND

SANDY SILT

SILT

grades westward into a zone of silty sand which extends from Palos Verdes Hills to Malibu, but has its greatest areal extent in the north. South from the city of Santa Monica to the northern edge of Redondo Canyon, the silty sand is broken by three patches of olive green sand; a large area of gravel and rock; and is separated from the silty sand to the east by an irregular band of sandy silt that extends north from Redondo Canyon.

The silty sand in turn grades westward into sandy silt. With the exception of an irregular zone that extends north from the head of Redondo Canyon; this sediment type occurs west of the silty sand where it parallels the topographic trend of both submarine canyons.

The finest sediment type in Santa Monica Bay is silt, which occurs in both submarine canyons and along the basin slope. A large area of silt occurs in Redondo Canyon in the midst of the sandy silt. In Santa Monica Canyon the silt extends eastward coincident with the topographic trend of the canyon. In this same general area, a rather narrow tongue of silt projects shoreward toward Malibu. The effect of the topography on the distribution of this sediment type in Redondo Canyon is not as apparent as it is in Santa Monica Canyon.

The normal decrease in grain size from sand nearshore to silt offshore is modified by the presence of gravel near the center of the bay on the outer shelf. This grades into a sandy silty gravel near Santa Monica Canyon. With three

exceptions, most of the samples outside the gravel area between the two submarine canyons contain less than 50% gravel (Fig. 14). Samples collected with the snapper sampler within the gravel area generally contain less than 50% gravel, although those near rock outcrops are composed of nearly 100% gravel. This fact, in conjunction with the abundance of gravel in cores and biological hauls, suggests that elsewhere in the bay the gravel is partly or completely covered or dispersed with finer sediments as shown schematically in Figure 15. In this diagram, a hypothetical east-west cross-section is shown across the gravel area. The boundaries of the gravel area indicated in the diagram were determined by dredging. Because the gravel is covered in part by finer sediments which are lost during dredging, the uniform distribution of the gravel shown in Figures 13 and 14 probably does not actually exist.

Sand, Silt, and Clay in the Sediments

In addition to the other charts showing many of the characteristics of bottom sediments in Santa Monica Bay, contour charts showing the proportions of sand, silt, and clay in the sediments are presented in Figures 16, 17, and 18. The distribution patterns of these components are not discussed because they repeat information contained in other charts, such as bottom sediment types (Fig. 13), and only tend to bear out and re-illustrate those conclusions. Their main use is as a reference to better visualize the nature of the sediment in each portion of the bay. In this respect, as the charts show only the proportions of sand, silt, and

Figure 14. Distribution of gravel in Santa Monica Bay.

Figure 15. Hypothetical cross-section of the rock and gravel area.

HYPOTHETICAL CROSS SECTION OF
THE ROCK AND GRAVEL AREA

Figure 16. Per cent sand in the bottom sediments of Santa Monica Bay.

SANTA MONICA BAY

PER CENT SAND

300 FT. BOTTOM CONTOUR

Figure 17. Per cent silt in the bottom sediments of Santa Monica Bay.

SANTA MONICA BAY

PER CENT SILT

300 FT. BOTTOM CONTOUR

Figure 18. Per cent clay in the bottom sediments of
Santa Monica Bay.

SANTA MONICA BAY

PER CENT CLAY

300 FT. BOTTOM CONTOUR

clay, they should be used in conjunction with Figure 14 which shows the location of samples containing gravel. Gravel percentages were not contoured, as the samples with gravel are few in number, and the extent of the distribution is not as general or as well-known as that of the other sediment components. In addition, much gravel apparently is distributed over the entire bay at various depths below the surface sedimentary cover.

Coarse Fraction

Properties of the sand fraction of sediments, such as mineral assemblages, distinctive minerals, content and type of organic remains, size, and shape can be used to gain an understanding of the depositional history and source of sediments. The sand fractions of all sediments collected in Santa Monica Bay were examined with a binocular microscope. From the mineral assemblages and distinctive minerals or components, the following six distinct sand types were established: (1) fine quartz-feldspar sand, (2) rock-fragment sand, (3) glauconite sand, (4) phosphorite-glauconite-shell sand, (5) shell sand, and (6) red sand (Fig. 19). As the classification into types is often based only on distinguishing components, the areas of occurrence are not considered mineral provinces, but rather as areas having accumulations of distinct minerals or mineral assemblages.

Figure 19. Distribution of coarse fraction types in Santa Monica Bay.

Fine Quartz-Feldspar Sand

Description

The fine quartz-feldspar sand is a fine or very fine angular sand composed primarily of quartz and plagioclase, with orthoclase and heavy minerals making up only a minor portion of the sediment. There is an average heavy mineral content of 2.4%, and a range from 0.5 to 6.7%. The most abundant heavy minerals are augite, hornblende, epidote, biotite, and magnetite (Table I). Biotite is exceptionally prominent in the offshore silts and sandy silts where it is the most abundant heavy mineral in the sand.

The primary light minerals are quartz and plagioclase, with quartz making up 49% of the fraction and plagioclase 42%. Orthoclase averages 9%. The range of values for light minerals are 49 to 60% for quartz, 30 to 49% for plagioclase, and 2 to 25% for orthoclase.

Authigenic minerals are rare. Glauconite, when present, is restricted in areal extent and limited to amounts less than 10%. Phosphorite occurs only in traces.

The most abundant organic constituent of these sands are Foraminifera, which are present in all samples in varying amounts. On the outer slopes of the bay, Foraminifera comprise nearly all the calcium carbonate in the sediments. Here, the percentage of calcium carbonate approaches the percentage of detrital material until in some areas, the sand grades into shell sand. Other organic constituents of the sands are Radiolarians, diatoms, and echinoid spines, which in all cases are minor in occurrence.

TABLE I

MINERALOGY OF SAND FRACTIONS
OF TWO SEDIMENT TYPES

Sediment Type	Fine quartz-feldspar sand (ave. of 16 samples)		Rock-fragment sand (ave. of 4 samples)	
Mineral frequencies	quartz	51.6%	quartz	49.8%
	plagioclase	40.4%	plagioclase	48.5%
	orthoclase	8.6%	orthoclase	1.7%
Per cent of total sample of specific gravity less than 2.9		96.4%		87.7%
	augite	30.2%	hornblende	29.8%
	hornblende	28.6%	rock fragments	25.0%
	epidote	15.4%	epidote	19.8%
	biotite	9.3%	magnetite	15.7%
	magnetite	4.9%	augite	7.0%
	zircon	1.7%		
	topaz	1.1%		
	less than 1 per cent		less than 1 per cent	
	chlorite		zircon	
	ilmenite		ilmenite	
	apatite		topaz	
	garnet		garnet	
	collophane		actinolite	
	titanite		tourmaline	
	actinolite		hypersthene	
	fluorite		enstatite	
	glaucophane			
	spinel			
	anatase			
	barite			
	kyanite			
	tourmaline			
	hypersthene			
	rutile			
	andalusite			
	glauconite			
	rock fragments			
	basaltic hornblende			
Per cent of total sample of specific gravity greater than 2.9		3.6%		12.3%
Total		100%		100%

The rounding of the detrital quartz, feldspar, and heavy minerals of these sands is 0.1. Sphericity of this material ranges from 0.70 to 0.80. Organic debris and authigenic minerals are well-rounded and highly spherical. These characteristics are inherent from their mode of formation. Broken shell material is generally angular and exhibits low values of sphericity.

Occurrence

Fine quartz-feldspar sand is the most widely distributed sand type in the bay (Fig. 19). It covers most of the area of the shelf and forms the major coarse fraction of the sediment deposited in the two submarine canyons and on the offshore slopes. Even in areas designated as glauconite sands, as much as 70% of the sediment may be of the quartz-feldspar type, and where the content of calcium carbonate increases by an abundance of Foraminifera, the detrital mineral grains are mainly quartz and feldspar. Again, on the offshore slopes, where median diameters are small, the coarse fraction of the sediment is generally fine quartz-feldspar sand.

The physiography of the shelf areas where this sand type occurs is generally an area of smooth micro-relief.

Rock-fragment Sand

Description

This sand is medium grained, subangular and contains rock fragments that generally are particles of dark schist and fine-grained igneous rock. The rock fragments are accessory, however, for the bulk of the sand is made up of quartz

and feldspar. The average heavy mineral content of these sands is 6.2% with a range of from 2.6 to 21.3%. The most abundant heavy minerals are rock fragments, magnetite, hornblende, and epidote. Proportions of quartz, plagioclase, and orthoclase show fairly constant relationships with an average value of 50% for quartz, 49% for plagioclase, and 1% for orthoclase. Foraminifera and shell fragments are present in these sands, but are not abundant.

Rounding of the grains shows a wide range, with the larger particles generally showing some degree of abrasion. This characteristic is a distinguishing feature of these sands. The range of rounding is from .10 to .60, and the sphericity ranges from .70 to .80.

Occurrence

Rock-fragment sand occurs in linear patches nearshore between the Hyperion Outfall and Santa Monica, and on the north side of Redondo Canyon where it lies in a depression trending north from the canyon. The largest occurrence in areal extent is on the outer portion of the shelf at the head of Santa Monica Canyon. This accumulation covers the entire head of the canyon and extends south into an area shoreward of the gravel and rock on the central shelf projection. Deposits of rock-fragment sand result in high median diameters and in sediments which have 80% or greater sand content.

Red Sand

Description

The red sands are coarse and subangular with a characteristic red stain on the grains similar to that on the fragments of some present day dune or beach sands. The mineralogy of the red sand is similar to that of the rock-fragment sand and the range of heavy mineral percentages is from 1.3 to 8.8%.

The red sands nearshore south of Redondo Canyon are different in appearance from those north of the canyon. The former characteristically have a brown color and a considerable amount of shell fragments. In the northern portion of the bay, a reddish color is more apparent and shell material is generally minor in amount. Shell fragments occurring in both areas show some signs of wear and the rounding of all fragments ranges from .20 to .40. The sphericity coefficient ranges from .70 to .80.

Occurrence

Red sand in the northern portion of the bay is always associated with rock fragment sand where it occurs as small isolated patches. It is nearshore in all cases except for one occurrence where red-stained minerals were recovered from the offshore deposit of rock-fragment sand.

South of Redondo Canyon the red sand occurs in a large linear deposit which parallels the shoreline and lies close to shore.

Shell Sand

Description

The shell sands are designated as those primarily composed of shells or shell fragments with fine quartz-feldspar sand as the host sediment. Sands with abundant shell material and associated authigenic minerals are excluded from this type. The organic remains, generally tests of Foraminifera, are often broken. The roundness of the shells ranges from .10 to .40, depending on whether or not they are broken, and the sphericity ranges from .70 to .80. The accessory detrital material is angular.

Occurrence

The shell sands are limited to patches occurring at the outer ends of the submarine canyons. They represent the accumulation of shells as the coarse fraction of sediments in offshore areas where the supply of coarse detrital material is small.

Phosphorite-Glauconite-Shell Sand

Description

The composition of this sand is extremely variable, but the association of phosphorite, glauconite, and shell fragments is so distinct that it warrants classification as a type. Quartz, mica, and rock fragments occur in the sand as detrital particles in minor amounts and the average heavy mineral content of the sand is 2.5%. The minimum percentage is 0.6% and the maximum is 6.7%, as glauconite and phosphorite generally

separate with the light minerals. The shell material present has fragments of the larger shelled animals in addition to the tests of Foraminifera.

The phosphorite shows a wide range of rounding (.50 to .80), as do the smaller grains of glauconite (.70 to .80). The sphericity of both minerals is from .80 to .90. Shell fragments are angular, generally with rounding values of .10 and a sphericity range from .70 to .80. Tests of Foraminifera which occur whole, are well-rounded. However, when the tests are broken, their rounding is in the same range as that of other shell fragments. Detrital minerals in these sands are generally angular.

Occurrence

Phosphorite-glauconite-shell sand is found covering the entire shelf projection between the two submarine canyons (Fig. 19). They are associated with the area of rock and gravel and also occur as the coarse fraction of all the silty sand and sandy silts on the outer shelf seaward of the gravel areas. A small area near the edge of the shelf south of Redondo Canyon is also covered by this sand type.

Glaucinite Sand

Description

The proportion of glauconite in this sand type ranges from about 20% to nearly 100%. Even though the quantity is highly variable, all sediments in which glauconite is a prominent constituent are included as glauconite sand. The

accompanying detrital material is generally fine-grained and cannot be differentiated from fine quartz-feldspar sand. The average heavy mineral content is 2.4% with a minimum of 0.9% and a maximum of 4.5%. Shells and shell fragments included in the sediment are generally the tests of Foraminifera. Phosphorite may occur, but it is limited to trace amounts, probably because the sediment is fine-grained.

The glauconite is dark green to light brown in color. It has a globular form, often with surficial suture-like markings which allow recognition of either internal casts of Foraminifera or coprolite casts. The glauconite grains range in roundness from .70 to .80 and in sphericity from .80 to .90. The associated detrital material is angular as are shell fragments. Whole shells, on the other hand, are well-rounded.

Occurrence

On the shelf and slope north of Santa Monica Canyon, a large patch of glauconite sand occurs in which the glauconite represents 20-30% of the material; the remainder being fine quartz-feldspar sand. On the basin slope off the outer shelf, glauconite sands virtually ring the entire area of phosphorite-glauconite-shell sand. Here the sand contains the highest amounts of glauconite and some of the sand fractions are composed almost exclusively of this mineral.

A small accumulation of glauconite sand occurs along the outer edge of the shelf and on the slope south of Redondo Canyon. The sand on the slope has a low glauconite content and is, therefore, similar to those sands on the shelf and

slope north of Santa Monica Canyon. The sand on the shelf south of Redondo Canyon contains a high percentage of glauconite and is similar to the material on the slope off the outer shelf.

The accumulation of glauconite sand is limited to the zone of variable micro-relief on the outer edge of the shelf and on the basin slopes.

Median Diameters

Definition and Significance

The median diameters of the bay sediments have been determined from graphs of the cumulative frequency by weight of the diameters of particles occurring in the sediment samples. The median diameter is the diameter of the central grain separating equal weights of particles coarser and finer than the median grain.

The median diameter can be used to determine the manner of formation of a sediment as it relates to the strength of currents which transport and deposit the individual particles. However, transportation and deposition of sediments are complex procedures with many variables, and the relation between median diameters and the agencies of transportation and deposition are too little known at present to allow rigorous analysis in this fashion. The main use of median diameters is to indicate the relative size of the sediment for mapping purposes, and for the determination of the distribution patterns which can be used in conjunction with other components, such as composition. In this manner, known processes in the ocean environment can be related to the occurrences of different types of sediment.

Distribution of Median Diameters

An isopleth map of median diameters of the bottom sediments in Santa Monica Bay is shown in Figure 20. In constructing this map, information from samples obtained with an underway sampler was not used, as the finer portions of material collected with this device are partially washed away during the sampling process. Samples of sediment collected while dredging for rocks were not used for the same reason. Results of the analyses of cores were also not used for this map. Elimination of the foregoing types of samples left 364 samples available for the preparation of this chart.

There are important limitations in the interpretation of the contoured information in Figure 20. The first is that the contour interval is geometric, rather than arithmetic, using boundaries of Wootworth grade sizes as the contour values (2, 1, $\frac{1}{2}$, $\frac{1}{4}$, etc. mm); and, secondly, there is a decrease of the number of samples with increasing water depth. In Figure 21 is a cumulative curve of the percentage of samples with depth which indicates the sparsity of samples at the greater depths. Seventy one per cent of the samples were obtained from the shelf at depths less than 300 feet and the remaining 29 per cent was from depths greater than 300 feet. Thus, the contours of the median diameters are based on successively decreasing amounts of information with increasing depth.

Median Diameters of Shelf Sediments

Offshore on the outer shelf, median diameters are relatively high and have an irregular distribution. This portion of the shelf contains extensive rock and gravel (Fig. 13) which are also

Figure 20. Isopleth map of sediment median diameters.

SANTA MONICA BAY

ISOPLETH MAP OF
MEDIAN DIAMETER IN MM.

300 FT BOTTOM CONTOUR

Figure 21. Cumulative curve of the percentage of samples in Santa Monica Bay.

contoured. However, these contours are based on only a few snapper samples. Cores for foundation studies indicated that the gravel extends a considerable distance towards shore, but lies under the band of coarse sediment inshore from the gravel. This coarse sediment is a thin cover, 6 to 10 inches thick, over the underlying gravel. From the sediments collected by a snapper sampler in the rock and gravel area, it is evident that at least a portion of the zone has some fine sedimentary material mixed with the coarser fragments. Due to the variability of sediment in this zone, and the paucity of samples, the exact sedimentary pattern cannot be completely defined.

Inshore from the central shelf projection, or the outer shelf, the sediment is roughly banded parallel to the coast. The outer band of sediment is coarse and extends along the head of Santa Monica Canyon and across the inshore side of the outer shelf. Shoreward from this is a pattern of finer sediment extending northward from Redondo Canyon. North of the tip of this deposit there are patches of fine sediment which bridge the gap between the southern zone of fine sediment and a tongue of this material which projects towards Santa Monica on the shelf off Malibu. This fine-grained sediment covers most of the northern shelf, except for a zone with slightly coarser fragments nearshore. South of Redondo Canyon the sediment also occurs in bands parallel to shore with very coarse sands close to the Palos Verdes Hills shoreline. To break this parallel pattern, between Venice and Hyperion close to shore are several tongues of coarse material which project seaward.

The gravels of the central shelf projection are relic and were deposited during a lower stand of sea level. However, the finer sediments occurring on the outer shelf are probably a recent sediment cover. The coarse fractions of this finer covering sediment contain authigenic minerals, such as phosphorite, and abundant shell fragments possibly indicating an environment of non- or slow deposition. Often this coarse fraction material is in the size range of granules and pebbles (2 to 64 mm in diameter). There must be sedimentation of fine-grained material here as in other portions of the bay, or at least over a portion of this area, but it may be slow enough to allow the formation of phosphorite and to favor the abundant growth of shelled animals. It is also possible that the phosphorite and shells are relics of a prior environment and are now being covered or reworked. Then too, the topography of this area consists of small highs and depressions of low relief (Fig. 8). Gravel and rock may be exposed at the highs with sediment accumulating in the lows. The high areas may be the loci of formation of phosphorite and the places of growth of shelled animals which are subsequently swept away and added to sediment accumulating in depressions.

The coarse material at the head of Santa Monica Canyon and on the shelf behind the central projection has been identified from its coarse fractions as being mainly relic sand with a low silt and clay content. This sediment is probably an old nearshore deposit in which some silt and clay accumulated with the sand. The tongues of coarse material nearshore in the vicinity of Venice and Hyperion

also have coarse fractions which have been identified as relic material. These are likely old beach ridges or near-shore deposits associated with a rising sea level. The intervening band of fine grained material which has a coarse fraction composed of fine quartz-feldspar sand is evidently sediment being deposited at the present time. This sediment has either filled in a low area behind an older deposit farther out on the shelf or has been deposited across the variable topography of an older series of deposits formed by an encroaching sea to create the smooth topography of the shelf (Fig. 9). The inner shelf appears to be a depositional apron, apparently formed by filling in of irregularities and making a smooth plain since the last lowering of sea level.

Fine material is kept from being deposited in the near-shore zone by the action of waves. The patch of fine-grained material near the Hyperion outfall, reported at this location by divers, is probably due to the deposition of sludge from the outfalls, which is relatively rapid so that all of the fine material cannot be removed.

Normal deposition of fine-and medium-grained marine sediments is taking place on the shelf off the Malibu coast and the median diameters decrease outward as a result. A clue to the areas where marine sedimentation is taking place at present is offered by a graph of median diameters related to depth (Fig. 22). In the depth interval from 125 to 175 feet, which is the depth range of the band of fine sediment on the central shelf, and also the depth range in which

Figure 22. Graph of median diameters of bottom sediments plotted against depth.

material of similar size range occurs on the shelf off the Malibu coast, the median value and the arithmetic mean of the median diameters are almost identical. Also, the range of values for this parameter are not extreme. However, the values for sediments in other depth ranges are widely divergent, where considerable relic material is known to exist and where there are abundant organic remains. The effect of relic material is not evident in the depth range of 125 to 175 feet as it is in all other depth ranges of the shelf. This, then, is the depth zone on the shelf where sedimentation is probably taking place at the present time and where this Recent material has covered older deposits.

The coarse sediment occurring nearshore on the shelf south of Redondo Canyon has been identified as relic red sand which is possibly a submarine outcrop of the Palos Verdes formation. This may be kept free of Recent sediments by currents which flow from the center of the bay impinging against the coast in this area or by the action of waves in shallow water. The outer portion of this shelf is evidently an area of deposition. The sediment there contains coarse fractions of authigenic minerals and shell fragments similar to the coarse fractions of sands on the outer shelf. Currents sweeping over this portion of the shelf may create conditions of slow or intermittent deposition and a removal of fine-grained sediment similar to that postulated for the central shelf projection as discussed later in the report.

Median Diameters of Sediments on the Slopes and Canyons

On the offshore slope below the shelf, basin slope, there is a fairly regular decrease of median diameters with depth. Isopleth lines of median diameters usually show the same general pattern as topographic contours. However, this pattern is interrupted at places by small patches of sediment which are coarser or finer than the surrounding sediment, which are the result of slumping on these slopes. Emery and Terry (1956) have shown that the topography of the basin slope of the Palos Verdes Hills is made up of innumerable small landslide scars, and that the sediments themselves on the slope and at the base of the slope show evidence of slumping. The same processes are undoubtedly active on the basin slopes and the slopes of the submarine canyon in Santa Monica Bay.

The sand fraction of the sediment on the slope off the outer portion of the central shelf is a phosphorite-glaucinite-shell sand, the same as the sand portions on the shelf above. Thus, it evidently has been derived by slumping of material or is winnowed from the outer edge of the shelf. The same sand fraction is present in the patch of coarse sediment in the bottom at the mouth of Redondo Canyon. It is also similar to the material occurring on the shelf above. Isolated patches of fine material on the slopes may be areas where fine sediment is building up under conditions of normal deposition.

The submarine canyons generally contain a tongue of fine-grained sediment along the axes of the canyons. This is particularly true in Redondo Canyon where fine-grained sediment lies close to shore in the upper end of the canyon. The

water in submarine canyons below the surface of the surrounding shelves is relatively quiet. Here, fine-grained sediments can accumulate. Coarser sediments that are transported across the shelf also have a tendency to accumulate in depressions such as these canyons. Along the axis of a canyon, finer material is often interspersed with coarse material that has slumped down the canyon walls or has been trapped as noted above. This is the case in Redondo Canyon (Fig. 13).

Fine-grained deposits in the submarine canyons may be carried there by density currents. The axis of the pattern formed by the median diameters in Santa Monica Canyon is shifted to the north from the topographic axis of the canyon. This may be due to the fact that the south wall of the canyon is steeper than the north slope, resulting in considerable slumping of material from the south slope, but allowing sediment to accumulate normally on the north side with a minimum of movement by slumping.

Relation of Median Diameters to Depth

The expected pattern of sedimentation on a continental shelf, and to some extent on the steeper slopes at the edge of the shelf, is that median diameters will decrease with depth. This is due to increasing distance from shore, the source of the detrital material, and to a reduced competency of transporting agencies with depth. Thus, an ideal isopleth map of median diameters in this environment should show them decreasing with depth and more or less closely related to submarine topography. Detrital material of sand size which is moved by traction and saltation should show an offshore decrease,

whereas silt and clay which are mainly carried in suspension should increase in an offshore direction.

There are certain known factors related to the composition of the sediment which will disturb this theoretical gradation. These are: (1) the occurrence of authigenic minerals having sizes not related to depositional mechanics of the host sediments, (2) shells and their fragments occurring in a sediment which are formed by local organic processes and bear no relationship to the transported detrital components where they occur, and (3) relic accumulations which were formed during a previous depositional period, usually that of a lowered sea level, and have not been covered or removed during subsequent periods of sedimentation.

The distribution of relic sediments, authigenic minerals, rocks, and organic remains in the sediments of Santa Monica Bay often causes a general offshore increase, or a local increase in grain size as compared to the surrounding material. The relationship of these factors to the general pattern of sedimentation of the shelf and slopes is shown in Figure 23, which is a graph showing the variation of median diameters with depth. The diagram consists of the arithmetic mean, median, and highest and lowest values of median diameters of the deposits in each of a series of depth ranges. It should be noted that the axis of this diagram indicating size is logarithmic. The deeper depth intervals were made greater than those at shallow depths to include a comparable number of samples because of the decreasing proportion of samples with depth as noted earlier. The arithmetic mean is the

average and the median is the central value of all median diameters in the depth interval. In each interval, the mean usually becomes greater than the median as the spread of values larger than the median increases.

The median and mean of median diameters increase with depth in the interval from 25 to 100 feet. Also in this interval, the values greater than the median are spread considerably more than those that are smaller. This increase with depth and exaggeration toward high values is due to the fairly large amounts of relic sediment, particularly coarse red sand, which occur in this depth range. From 100 feet to 175 feet the median diameters show a decrease. In the range from 125 to 175 feet, the median and mean values for the median diameters are almost identical and the highest and lowest values show a narrow range. These depths correspond to the most widespread areas of fine-grained sediment on the shelf and the change of character in the curves indicates present day sedimentation and contemporary covering of older deposits as has been discussed in preceding sections. The effect of relic material evident in other zones is not shown in this depth zone. From a depth of 175 feet to 300 feet, the median diameters show a general increase and a wide spread of values higher than the median due to the occurrence of relic material, authigenic minerals and rocks, and coarse shell fragments in this depth range. The coarse gravels, indicated by dredging, cannot be shown on this diagram, since complete samples were not retained for analysis, but their effect would be generally to cause a high maximum value of

median diameter in this range and increase the arithmetic mean while the median and low values would remain almost the same.

Below the shelf break the effect of slumping is clearly shown. The values show a decrease to a depth of 500 feet and in this range there is still a wide range of maximum median diameters. In the interval from 500 to 1,000 feet there is a slight increase in the median value and the mean shows a sharp rise. This shows clearly the effect either of coarse material which has slumped into Redondo Canyon in a zone of generally fine-grained sediment and the median diameter of the samples of this slumped material forms the high maximum value in this range, or the possible effect of organic contribution. At depths greater than 1,000 feet the median diameters show a sharp decrease and the mean and median are nearly the same. Also, the maximum and minimum values are evenly distributed about the median. This indicates the existence of normal sedimentation in this region without visible effects of slumping. Undoubtedly slumping occurs, but is out of the range of delivery of coarse sediment from the regions of the shelf near the break. The slumping is probably of sediments of similar size ranges and its effect is not evidenced by any apparent anomalous pattern of distribution of sediment.

Sorting

Definition and Significance

The sorting coefficient (Trask, 1932) is computed from the cumulative curve of grain-size distribution. By definition,

the sorting coefficient is the square root of the ratio of the particle diameter representing 25 per cent of the sediment weight to that representing 75 per cent of the sediment weight, or $S_o = Q_{25}/Q_{75}$. It is, therefore, a dimensionless number which is an index of the degree of sorting of the sediment; or, in other words, the extent to which the particle diameters are spread on either side of the median diameter of the sediment. The sorting coefficient indicates the degree of uniformity of grain size and numbers close to unity indicate uniformly distributed grains in a sediment. In the system set up by Trask, sediments having sorting coefficients from 1.00 to 2.50 are well-sorted; those with sorting coefficients from 2.50 to 4.00 are moderately-sorted; and those greater than 4.00 are poorly-sorted. A sediment having a sorting coefficient of 1.5 is not twice as well sorted as one having a value of 3.0, because the coefficient is geometric. The sorting of sediments is directly related to the median diameter, and in some cases, listed by Inman (1949), sediments having a median diameter of 0.18 mm are the best sorted; the sorting being poorer for sediments both larger and smaller than this value. However, in Santa Monica Bay, the sediments with median diameters from .05 mm to 0.10 mm are the best sorted, even though the relationship holds that coarser and finer sediments have poorer sorting. This relationship is shown in Figure 23 which has a point plotted for each sediment sample with the median diameter as the abscissa and the sorting coefficient as the ordinate. On this diagram there is a prominent grouping of points for well-sorted sediment in the

Figure 23. Sediment sorting coefficients plotted against median diameters.

.05 to 0.10 mm size range. This range of median diameters includes all the fine sediment of the shelf in the area which has been interpreted as the zone receiving most sediment at the present time. This probably accounts for the apparent well-defined minimum grouping of sorting coefficients for these sediments, for most coarser sediments in the bay contain some relic material relating them to a previous stage of deposition, and also contain authigenic minerals and shell fragments. In addition, most finer sediments occur on slopes where slumping and sliding of sediment take place and contain numerous Foraminifera in their coarse fraction. These components and occurrences would tend to indicate that the sorting of these sediments is unrelated to the mechanics of sedimentation which have caused deposition of the well-sorted sediment on the shelf. It should be remembered that most statistical theoretical studies deal with sediments from a single source which have been transported and deposited by a single uniform process.

Sorting of Sediments in Santa Monica Bay

The sorting of sediments in Santa Monica Bay is shown in Figure 24. On the shelf, most of the sediment is well sorted with small patches of moderately-sorted sediment close to shore in the vicinity of Venice, Hyperion and the Palos Verdes Hills. Moderately-and poorly-sorted sediment occurs on the central shelf projection and adjoining areas and at the head of Santa Monica Canyon. Two relationships are evident, (1) the moderately-or poorly-sorted sediments tend to

Figure 24. Sorting of sediments of Santa Monica Bay.

SANTA MONICA BAY

SORTING

300 FT BOTTOM CONTOUR

AREAS OF WELL SORTED
SEDIMENT (SQ. < 2.50)

AREAS OF MODERATELY
SORTED SEDIMENT
(SQ. 2.50-4.00)

AREAS OF POORLY SORTED
SEDIMENT (SQ. > 4.00)

be among the coarsest on the shelf, and (2) moderately-and poorly-sorted sediments occur among the relic sands and sediments containing an abundance of authigenic minerals and shell fragments.

The nearshore relic materials, which are both red sands and rock fragment sands, often contain significant amounts of gravel or silt and clay. Both cause a wider spread of the grain-size distribution and create the areas of moderately-sorted sediment. The moderate sorting of these sediments caused by gravel is inherited from their original period of deposition. The sorting value resulting from the silt and clay may have either originated during the last stages of deposition, or as a result of the accumulation more recently of a thin cover of fine-grained detritus over the relic material. Moderate and poor sorting in the offshore sediments containing relic sands or gravels are probably due to the same reasons. Poorly-and moderately-sorted sediments on the outer shelf have coarse fractions composed of authigenic minerals and shell fragments and a patchy distribution similar to that observed in sediment size. Any processes which tend to concentrate coarse material, such as winnowing away of fine material or removal of this material from highs and subsequent deposition in depressions, create "depression" sediments which are poorly-and moderately-sorted, and "high" sediments which may be well-or moderately-sorted. The intervening purely detrital sediments on the central shelf and those on the shelf off the Malibu coast are all well-sorted.

Areas of poorly-or moderately-sorted sediments on the basin slopes below the shelf are more widespread than on the shelf. Here the moderately-and poorly-sorted sediments are generally in the areas of the finest sediment. Slumping and sliding are important here and probably are responsible for the existing sorting. The accumulation of Foraminifera as the coarse fraction of sediments may alter the grain-size distribution enough to cause moderate to poor sorting. In addition, silt and flocculated clays may settle out together, and yet represent a wide range of particle sizes.

Sediment along the courses of the submarine canyons is usually moderately or poorly sorted. This may be caused by the movement of sediment through the canyons by slumping or sliding, both along the axis and down the side slopes.

Relation of Sorting to Depth

Figure 25 is a graph of the average and median of the sorting coefficients by depth intervals. The variation of the sorting of sediments with depth is similar to that of median diameters. Generally, the arithmetic mean of values in each depth range is greater than the median, which indicates a wider spread of values toward poorer sorting.

A peak occurs in the curve in the 51-75 foot range where patches of moderately-sorted sediment are located. From this depth to 175 feet the curve is fairly uniform. This depth range is over that portion of the shelf where most present-day sedimentation probably occurs. Another peak is noted in the 226-250 foot interval. This is due to the poor sorting

Figure 25. Sorting coefficients plotted against depth.

in relic sands and gravels, and in sediments containing authigenic minerals and shell fragments. There is a tendency for the sediment to become better sorted at 300 feet which is approximately at the shelf break. This may be due to turbulence at the edge of the shelf which would tend to create a better-sorted sediment. The curve is fairly uniform to a depth of 1,000 feet and then has another peak due to the relationship of poor and moderate sorting to fine grained deposits on the outer slopes.

Calcium Carbonate

Origin of Calcium Carbonate

It is believed that all, or practically all, of the calcium and magnesium carbonates in sediments are due to the accumulation of shells. The examination of sand fractions of the sediments from Santa Monica Bay indicates that the most abundant organic remains are the tests of Foraminifera. However, in some areas, notably on the central shelf projection and the shelf south of Redondo Canyon, fragments of larger shelled animals constitute a considerable proportion of the sediment.

Distribution of Calcium Carbonate

Percentages of calcium carbonate in the sediments are shown in Figure 26. The percentage increases in an offshore direction, being low over most of the shelf and slightly higher on the offshore slopes. The exceptions to this distribution are the extremely high percentages found in the patches

Figure 26. Calcium carbonate content of the sediments
of Santa Monica Bay.

SANTA MONICA BAY

1 0 1 2 3
STATUTE MILES

BOTTOM CONTOURS IN FEET

PER CENT

CALCIUM CARBONATE

> 50 %

on the outer shelf between Santa Monica and Redondo Canyons. This is illustrated in Figure 27 in which average values of calcium carbonate percentages in each of a series of depth intervals are plotted with increasing depth. The great increase of the average percentage in the 201-300 foot depth range is due to the large amounts of calcium carbonate occurring in the sediments on the central shelf projection.

The high concentration of shells on the outer shelf is due to (1) ecological conditions which are more favorable to the growth of shelled organisms, (2) winnowing of sediment finer than the shells, (3) the low supply of terrigenous sediments in this area, or (4) nondeposition in this area. As pointed out elsewhere in portions of this report, this region is probably an area of nondeposition or very slow accumulation of detrital material. The main cause for the increase in the percentages of calcium carbonate then is due to winnowing or nondeposition of fine material. Since the shells are relatively coarse they can accumulate in abundance and thus constitute a high proportion of the sediment in this area.

The high values of calcium carbonate on the shelf south of Redondo Canyon result from the red sand which contains a large number of shell fragments. This sediment is possibly a submarine outcrop of the Palos Verdes sand, an Upper Pleistocene age terrace deposit which contains a great quantity of shell debris.

The general offshore increase in calcium carbonate in the other parts of the bay is due to the diminishing supply

Figure 27. Graph of CaCO_3 versus depth.

of coarse detrital material derived from the land areas; therefore, there is less dilution of calcareous material offshore. Thus, the amount of CaCO_3 is inversely proportional to the supply of inorganic detritus at any point on the bottom. The size of calcareous material is not dependent upon currents and turbulence to the extent that terrigenous sediments are, so that skeletal remains of sand-size and larger may accumulate where currents are very weak. Conversely, the coarseness of some of the shells allows this material to accumulate where fine grained material cannot, i.e., in regions of strong currents and turbulence. In deeper seaward areas, shells (primarily the tests of Foraminifera) form the major portion of the coarse fraction of the sediment, probably as a result of a small contribution of detrital material which in other areas would normally dilute the organic contribution.

Organic Matter

Almost all elements found in organic compounds are also found in inorganic material. As a result, it is difficult to separate pure organic matter. Since carbon is the principal constituent of organic matter, it is generally used as an index of the amount of organic material. The abundance of organic carbon varies between 50 and 60 per cent in organic debris and if the total quantity of organic matter is desired, the per cent carbon must be multiplied by an appropriate factor which varies between 1.7 and 1.9. The choice of the factor is difficult to make because the value depends upon

the environment under which the sediment was deposited and the type of plants and animals from which it was derived. Furthermore, sediments containing appreciable quantities of sewage may require an entirely different factor than those given above. For these reasons, the per cent organic carbon is used in this report to discuss the relative amounts of organic matter, and these values must be multiplied by some factor (such as the above) if the total quantity is desired.

Source of Organic Matter. The source of organic debris in the ocean is both the land and sea. However, since the amount of organic matter brought to Santa Monica Bay by streams is negligible, it can be neglected. An important local source is the sewage discharged into the bay, but the most important source is phytoplankton which is the basic nourishment of all life in the ocean. Only a small portion of the organic material from the water survives the fall through the water or escapes consumption on the bottom by scavengers or oxidation. Sverdrup, et al. (1942, p. 929, 938) estimate that between 495 and 990 grams (dry weight) per square meter per year of organic production takes place in the waters off southern California. Emery and Rittenberg (1952) estimate that less than 1/16 of the organic matter produced at the surface of the sea escapes destruction during its travel to the bottom of the basins off southern California. Trask (1939) suggests that only 2%, or 20 grams per square meter per year of organic matter is deposited annually of an original 1,000 grams produced near the surface of the sea, and that under natural conditions sediments that have been

buried to a depth of one foot, on an average, have lost about 15% in organic content. The rate of destruction varies according to the rate of sedimentation. Thus, when deposition is slow, oxidation can be almost complete, whereas when sedimentation is relatively fast some of the organic matter escapes decomposition and is buried. This, of course, assumes that there is an adequate supply of oxygen and that aerobic conditions are present at the sediment-water interface in both instances.

Distribution of Organic Material in Santa Monica Bay.

The highest values of organic carbon in Santa Monica Bay are found beyond the shelf break and the lowest occur near shore (Fig. 28). There is a general increase in organic carbon with increasing distance from shore and with increasing depth. Exceptions to the offshore increase are at the head of Santa Monica Canyon where the organic carbon is low, and near Hyperion outfall where it is higher than the average in the nearshore region (Fig. 29). There is also a correlation between the organic carbon and submarine topography; the organic carbon being low in regions of elevations and high in depressions such as Redondo Canyon.

The organic carbon content for 155 samples ranges from 0.13 to 2.76%, averaging 0.59 for the shelf and 1.52% for the canyons and basin slope sediments. The overall average for the bay is 0.96%. Emery (1954) reported that the average organic carbon content for the continental shelf sediments off southern California was 0.44%, and 1.56% for the basin and canyon sediments (Table II). These values are similar

Figure 28. Organic carbon content of bottom sediments.

SANTA MONICA BAY

ORGANIC CARBON CONTENT

300 FT. BOTTOM CONTOUR

0.5% CONTOUR INTERVAL

Figure 29. Distribution of organic carbon with depth.

PER CENT ORGANIC CARBON

TABLE II

COMPARISON OF ORGANIC CARBON IN SEDIMENTS
OFF SOUTHERN CALIFORNIA

Environment	Emery, 1954	Santa Monica Bay
Mainland shelves	0.44% (av. of 22 samples)	0.59% (av. of 150 samples)
Basin slope	1.56% (av. of 30 samples)	1.52% (av. of 50 samples)

to those of Santa Monica Bay, suggesting that the effect of sewage discharge has not appreciably increased the average quantity of organic matter in the bay except near the outfall.

The distribution and quantity of organic matter in any region depends to a large extent upon the movement and physico-chemical nature of the overlying water, and the balance between organic and inorganic deposition. For example, the main cause for the offshore increase in organic carbon is the change in the texture of the sediments in a seaward direction. This is illustrated in Figure 30 in which per cent organic carbon is plotted against median diameter. The diagram clearly illustrates that as the grain size of the sediment decreases, the percentage of organic carbon rises. This relationship is so well established that Trask (1939, p. 434), knowing the type of sediment, has utilized empirical constants in order to make rough determinations of the percentage of organic matter in the sediment.

Detrital sediments and organic debris having the same densities will accumulate together. In the regions where sands predominate, i.e., in the nearshore zone, currents and turbulence usually are strong enough to wash away fine silt and clay as well as organic matter which is fine grained and is relatively light, so that it is easily transported by weak currents. Even if large fragments of organic debris were deposited in the nearshore zone, decomposition by oxidation or bacterial action would slowly break down the material into finer and finer particles which would probably be washed seaward and deposited in quieter water. The large

Figure 30. Per cent organic carbon plotted against median diameter.

pore spaces between sand grains in the nearshore region allows water to circulate with little difficulty and as a result, oxidation of organic matter occurs to considerable depths below the surface. The relatively low values of organic carbon in the nearshore region, therefore, are the result of an abundant supply of oxygen and associated bacteria that can penetrate the sediments, together with shifting of sediment by wave and current action. Such conditions facilitate decomposition and transportation of organic debris.

Organic matter having a density slightly greater than sea water can best accumulate in quiet waters where silt and clay particles are also being deposited. Fine-grained sediment also aids the preservation of organic matter because it is difficult for water to circulate through the small pore spaces of silt and clay particles.

It is noteworthy that the proposed discharge location is in the general region of nondeposition of sediments so that there probably is considerable motion along the bottom. This may have two important effects on the sewage: (1) redistribution of the sewage, and (2) faster oxidation of the organic matter.

The distribution of organic matter in sludge or effluent after it enters sea water at the point of discharge will depend upon: (1) the rate of flocculation or sedimentation, (2) the direction and velocity of currents and turbulence, (3) rate of decomposition, and (4) slumping and submarine landslides. If the organic matter, largely in the form of sludge but also suspended in the effluent would flocculate

immediately upon contact with sea water, the organic matter would initially be deposited over a relatively small area. Experiments have shown, however, that sludge generally does not flocculate immediately, and being lighter than sea water tends to rise.

Several observations have been made during a number of experiments on the reactions of sludge in sea water; namely, (1) sludge in the form of large "globs" rises towards the surface, but begins to disintegrate after rising only a short distance, (2) after the "globs" break up into smaller particles there is a tendency for the smaller pieces to settle very slowly towards the bottom, (3) colloidal (and perhaps clay size) particles do not always flocculate, but form a residual turbidity which lasts in quiet waters for periods in excess of 48 hours, (4) several experiments in which simulated thermoclines were used, indicated that the thermocline may not suppress the rising organic matter below the thermocline - apparently no matter how much temperature difference exists between the boundary layers.

The tendency for the sludge to rise in the experiments was due in part to the lighter density of the sludge, but it was also probably due to gas trapped in the large "globs". Once the gas was released by disintegration of the "globs", more surface area of the sludge was exposed which facilitated better flocculation. The above laboratory experiments may or may not simulate actual conditions in the ocean; however, the experiments did show the necessity of eliminating as much grease and gas from the sludge as possible.

Cores

Coincidentally with the collection of snapper and Hayward grab samples, a number of cores ranging in length from 14 to 68 inches were obtained in several localities. A total of 15 cores were collected along the proposed outfalls and at the head of Santa Monica Canyon. A description of the cores is given in the Appendix of this report.

Most of the cores along the traverse from Hyperion to the edge of the shelf are uniform, but marked changes in lithology occurred in some (Fig. 31). Close to shore the sediments are generally composed of sands and silty sands. In a few cases some shells mark the only vertical changes in lithology. Farther offshore the sediments are predominantly sandy silts, but gravel and other coarse sediments sometimes occur. The two cores at the edge of the shelf and on the basin slope contain sand and silty sands which are overlain by gravelly silty sand, sand with shell fragments, or by gravel. These cores on the outer shelf and on the basin slope are therefore unique since they have abrupt changes in lithology.

Two cores taken along the axis of the Santa Monica Canyon (3342 and 3345) have gravel and sandy gravel, but the other three are rather uniform in texture. Gravel, sandy gravel, and shell debris are common in all of the cores taken from the head of Santa Monica Canyon.

Additional cores and jettings were taken elsewhere in the bay and close to shore, near Hyperion. An examination of the logs show that the lithology varies greatly in a vertical

Figure 31. Lithology of gravity cores.

SANTA MONICA BAY

LITHOLOGY OF GRAVITY CORES

o CORE STA.

direction over most of the bay. Except for the uppermost few inches, or feet in a few logs, most cores do not show good core-to-core correlation. It is obvious that great variations in sedimentation have taken place over most of the bay. Some of the factors effecting the sedimentation in Santa Monica Bay and the significance of these changes in deposition will be discussed after considering the geologic structure and the source and transportation of sediments.

ROCK BOTTOM AREAS

The rocks of Santa Monica Bay can be divided into three groups; rocks in place (or bedrock), transported rock and gravel, and authigenic rock.

Rocks in Place

The rock outcrops rise as irregular and scattered mounds on the outer shelf south of Santa Monica Canyon, and occur in an elongated tract close to the Malibu shore as shown in Figure 13. The Appendix lists the samples of rock believed to be in place and describes their lithology. In addition to the samples obtained during the present survey, Emery and Shepard (1945) obtained a few samples of rock from the walls of both submarine canyons. The U. S. Coast and Geodetic Survey "smooth sheets" show rocky bottom along the Malibu coast and off Palos Verdes Hills. Johnson (1940b) made a detailed chart of the rocky (bedrock and gravel) seafloor in the nearshore zone along the coast of Malibu and Santa Monica. No rocks were dredged along this part of the coast during the

present survey, but Schupp (1953) studied the gravel that periodically washes up on the beach in this area so the general lithology of the material is known.

Siliceous and non-siliceous shales were the most abundant rocks recovered from the offshore area, followed in importance by mudstones, siltstones, and sandstones. Emery and Shepard (1945) recovered limestone and red rhyolite from Redondo Canyon, and dredged conglomerate, rhyolite, andesite, and granite from Santa Monica Canyon. They date the granite as Jurassic (?) on its lithologic affinity to granite outcrops in the Santa Monica Mountains. At least one sample collected by the Hancock Foundation (station 4321) was positively identified as being Upper Miocene in age (Lower Mohnian) and several other samples were dated as probable Miocene. Emery and Shepard also found rocks containing Foraminifera of Miocene, Pliocene, and Pleistocene age in a conglomerate dredged from Santa Monica Canyon.

A large amount of shale (both siliceous and nonsiliceous), mudstone, and siltstone was dredged from the rock and gravel area on the outer shelf. Many of the fragments were nearly covered, or bored through, by organisms such as pholads and echinoids. Few of the sedimentary rocks had diagnostic Foraminifera. Since pholads and most other rock boring organisms are generally restricted to the littoral zone, or relatively shallow water, where current and wave action is quite vigorous, the abundance of borings indicates that this area was at one time close to sea level.

One dredge haul (station number 3268) made on the outer shelf contained schist. Since the fragments were large and freshly fractured, it is probable that the dredge struck bed-rock. This dredge haul was somewhat unique in that all other hauls from this part of the shelf recovered only sedimentary rock or well-rounded gravel. None of the gravel was composed of schist, but occasional small fragments of schist were found adhering to pieces of shale.

Gravel

Most of the gravel on the shelf is well-rounded and ranges in size from granules to cobbles. It is composed mainly of igneous rock, but metamorphic and sedimentary rocks are also represented. The Appendix lists the transported rocks according to lithology, and Figures 14 and 32 show the areal distribution of gravel recovered from the surface of the sea floor.

Most of the sampling in the bay was done with a snapper sampler which gathers about two to four cubic inches of sediment. The Hayward grab, used for obtaining biological specimens, collects up to three cubic feet of sediment. The material collected by both sampling devices appeared to have similar characteristics, but after screening the samples obtained by the grab, there frequently remained considerable quantities of gravel which was not always recovered in nearby snapper samples. Most of the gravel does not exceed a few centimeters in diameter. Gravel is evident in the wash-borings made along the proposed and old outfall lines shown in Figure 31. From

Figure 32. Lithology of bedrock and gravel in Santa Monica Bay.

25'

118° 30'

35'

SANTA MONICA BAY

LITHOLOGY

55'

55'

.....300 FT. BOTTOM CONTOUR

LEGEND

- SH OUTCROP B TRANSPORTED
- RH RHYOLITE AN ANDESITE
- B BASALT
- G GRANITE GNEISS
- GR GRANITE
- GD GRANODIORITE
- D DIORITE
- S MICA SCHIST
- SL SLATE
- Q QUARTZITE QZ QUARTZ
- SS SANDSTONE SM META-SANDSTONE
- SH SHALE
- L SILICEOUS SHALE
- M MUDSTONE
- SI SILTSTONE
- P PHOSPHORITE (AUTHIGENIC)
- LS LIMESTONE LC LIMESTONE CONCRETIONS
- CN CONGLOMERATE C CHERT
- SNAPPER & UNDERWAY SAMPLER STA.
- HAYWARD GRAB STA.
- ▲ CORE STA. (AFTER EMERY & SHEPARD, 1945)
- DREDGE STA.

ROCK & GRAVEL BOUNDARIES
DETERMINED BY DREDGING

33° 50'

33° 50'

25'

118° 30'

35'

GR, RH
SL, SH
QZ, LS, C, P

GD, SH, LC, C, P, G, QD, S, SS

GR, CN, LS

SH, LS

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these considerations, gravel may be more widespread than is indicated on the surface sediment charts, but below the depth of penetration of a snapper sampler.

The gravel could either have been derived from outcrops on the outer edge of the shelf or from the land adjacent to the bay. The fragments are too large to be carried by present day currents or waves in overlying shelf water, so they must have been transported by streams or surf action in some previous geologic time of lower sea level. This conclusion was also reached by Shepard and MacDonald (1938, p. 213). The restriction of large patches of gravel to the outer shelf suggests that this may be the source area. However, the great diversity of lithology of the gravel probably indicates that streams carried at least part of the material from some inland source having a complex geologic structure. Whether the gravel was derived from erosion of the rock area on the shelf or by erosion of the uplands and transported to the area by streams during a lower stand of sea level is problematical. There is evidence, however, that the gravel is a relic sediment that was deposited in the early part of Recent time or in the Pleistocene period (Shepard and MacDonald, 1938; Revelle and Shepard, 1939). The large size of some of the cobbles and rock fragments, abundant pholad borings, high concentration of CaCO_3 , and the attachment of coral and bryozoans are taken to mean a long period of stability in the marine environment since the material was deposited.

Phosphorite

The only authigenic rock occurring in the bay is phosphorite. Almost every sample collected from the rock and gravel area on the outer shelf, as well as samples from other parts of the bay, contained phosphorite (Fig. 32). The phosphorite generally is in the form of nodules ranging in size from less than 2 mm to more than 10 mm. Some phosphatized mammal bones and shark's teeth were also recovered (Fig. 33). Dietz, Emery, and Shepard (1942, p. 929) report that the only shelves off southern California having phosphorite are off Santa Monica and San Diego, although it is common on banks and topographic highs far from shore. They report that the shallowest sample of phosphorite obtained was from the Santa Monica shelf in 240 feet of water, but one sample recovered during the present survey came from 140 feet of water. This may have been transported following formation, however.

Dietz, Emery, and Shepard (1942), and Dietz and Emery (1942) have shown that the phosphorite found off the coast of southern California is formed in situ by chemical precipitation of phosphate from sea water. They also note that Foraminifera of lower Middle Miocene age occur in large nodules on the outer shelf in Santa Monica Bay, and in others from the same general area there are fossils of Middle Miocene age (Luisian or Relizian).

Significance and Origin of Phosphorite

Phosphorite forms by the chemical precipitation of tricalcium phosphate from sea water. The precipitation depends

Figure 33. Photograph of phosphatized mammal bone.

upon the saturation of phosphate in sea water, which in turn is a function of the pH. Apparently slight changes in the physical-chemical or biological conditions near the bottom may cause a saturation of phosphate causing precipitation. The formation of phosphorite is apparently a slow process and consequently its presence indicates slow or negligible detrital deposition in the region where it occurs. Since some of the nodules in the bay area have grown to considerable size, they must represent a reasonably long period of nondeposition. The phosphorite generally occurs on the surface, not buried so that its occurrence here is indicative of either nondeposition or very slow sedimentation

Most of the nodules collected by Dietz, Emery, and Shepard contained a predominance of Foraminifera of Miocene age, and at one station a mixed fauna of Miocene and Pliocene ages. In several other samples, separate nodules and phosphatized cement of conglomerates contained Foraminifera of Quaternary age. These authors concluded that while a small proportion of the phosphorite must have a Quaternary age, the bulk of the phosphorite was formed during the Miocene period.

There are at least two ways in which the phosphorite could have formed during Miocene time and still be abundant on the sea floor: (1) the phosphorite formed during the Miocene on submarine highs which have been neither eroded nor covered by later deposition, (2) the nodules on the present sea floor may have undergone residual concentration from Miocene rocks. Dietz, Emery, and Shepard (1942, p. 841) point out some of the difficulties of both hypotheses. In the first

case, they believe it to be inconceivable that the Santa Monica shelf and canyons were eroded during the Miocene period. However, both the shelf and the walls of the canyons contain Foraminifera of Miocene age enclosed in nodules, and Miocene age rocks are on the shelf and probably in the canyons. The second hypothesis - residual concentration of Miocene age phosphorite nodules - perhaps is a better explanation, since it would account for the abundance of phosphorite on the Santa Monica shelf and in the walls of the canyons even though each may have been cut in relatively recent time. Neither hypothesis adequately explained the existing conditions; therefore, the authors presented two alternative possibilities to account for the Miocene age Foraminifera in nodules of Quaternary age: (1) phosphorite deposits formed by infiltration of phosphatic solutions into porous Miocene age formations with the replacement of some of the Miocene age material, (2) the phosphorite deposits may have been formed by enclosure of reworked Miocene age Foraminifera in nodules formed during the Quaternary. Thus, they tentatively conclude that possibly the nodules dredged off southern California were deposited on the present shelves, banks, and in the canyons during the Quaternary and that previously an abundance of Miocene age Foraminifera had been eroded or weathered out of the Miocene age formations and concentrated on the sea floor surface where phosphorite deposition took place.

No additional age determinations of the phosphorite dredged from Santa Monica Bay have been made so that the determinations by Dietz, Emery, and Shepard are the only

ones for this region. It is known, however, that rocks of Miocene age are on the outer shelf, and there is evidence that most of Santa Monica Bay was formed in relatively recent geologic time.

Character and Origin of Nondepositional Surfaces

From a theoretical point of view, there should be an even gradation from coarse to fine sediment when moving from the shore seaward. Numerous investigators, however, have noted the common occurrence of coarse sediments near the outer edge of shelves (Fairbridge, 1947). In addition, there are any number of places where bedrock crops out on a sea floor which, according to theory, should be covered by sediment. Many of these areas of nondeposition are known off the coast of southern California, so that surfaces of non- or slight deposition in Santa Monica Bay are not unique. However, even though many such submarine surfaces are known in many parts of the world, little is known of their origin. There can be no question that in most cases, sediments are transported at least as far as the nondepositional surfaces, but then either by-pass the surface or are deposited and later resuspended and carried away.

The following criteria are used as evidences of non-deposition: (1) rock outcrops exposed on the sea floor; (2) gravel at considerable distances from shore. Gravel introduced by streams cannot be carried far beyond the littoral zone. In fact, gravel frequently migrates shoreward if it is in the zone effected by wave action. Therefore, gravel in

deep water probably represents a deposit laid down in the geologic past; (3) The occurrence of rocks bored by organisms gives strong evidence of a littoral or shallow water environment at the time the rocks were inhabited by animals. If the depth is now considerably greater than the depth-habitat of the boring organisms, it must be presumed that sea level has risen and that little sediment has subsequently accumulated; (4) the presence of coarse terrigenous sands separated from the shore by finer sediments probably indicates at least two periods of deposition; (5) the presence of glauconite, phosphorite, and high percentages of CaCO_3 are indicative of slow or no deposition. On the other hand, much of the area in Santa Monica Bay which exemplifies the above criteria also has up to 30% silt and clay in the sedimentary material. Deposition, then, does occur, but is either extremely slow or is intermittent with a periodic resuspension of the material.

As pointed out by Fleming and Revelle (1939), and Revelle and Shepard (1939), the primary force necessary to transport sediment is the "static bottom friction" on sedimentary particles. If some force lifts a sediment particle even for a brief moment, then any resultant force (current or turbulence) acting in a constant direction, no matter how small its magnitude, will effectively transport the particle. On a topographic high, the net result would be a winnowing of the detrital material of a size determined by the force which is competent to put the particle in suspension. Thus, the sediment would be transported from a topographic high area to a

lower part of the sea floor by currents, turbulence, and gravity. The settling velocities for very fine sand (0.1 mm) at 20°C is 0.778 cm/sec. and for clay 0.000892 cm/sec. Since the settling velocities for particles of these sizes are low, they could be carried far before settling. The distance of transport would depend on the height above the bottom and the velocity of the transporting current.

Turbulent motion may be caused by waves or currents. In Santa Monica Bay convection currents resulting from the distribution of density are too small to produce any significant turbulence near the bottom. Revelle and Shepard (1939) believe that the chief transporting forces must be tidal and non-permanent eddying "slope" currents resulting from wind action. Although these currents produce no net transport of water, they are rapid enough even at considerable depths to generate pronounced turbulence. Turbulence thus produced tends to be strongest over banks and other obstructions. It is likely that such turbulence exists on the outer shelf in Santa Monica Bay. Current measurements and the analyses of slope currents at depths of 100 to 180 feet show that velocities of as much as 0.2 knot may occur on occasion.

The only data known concerning threshold velocities is the work by Hjulström (1939) and Inman (1949). The minimum threshold velocity necessary to erode sediments already deposited on the bottom finer than silt (1/16 mm) is about 35 cm/sec. (0.7 knot). It has been noted by several sedimentologists that particle sizes of about 0.18 mm (fine sand) require minimum threshold velocities, and that the threshold

velocity increases for sediments both finer and coarser than 0.18 mm (Inman, 1949). It takes a current velocity between 0.5 cm/sec. (0.01 knot), and 20 cm/sec. (0.4 knot) to keep sediment finer than silt in suspension, but if the velocity falls below about 0.5 cm/sec. the material will be deposited. Shepard (1948, p. 63) made 14 to 21-hour current measurements in Santa Monica Bay with a tripod resting directly on the bottom. Three current meters were superimposed on the tripod at 21, 51, and 126 cm above the bottom. He found few measurements over 10 cm/sec. and the maximum was 15.9 cm/sec., 84 cm above the bottom. One series showed extreme variability and the other series in the same general locality showed less variability but equally low maxima. Bottom current measurements by the Hancock Foundation over most of the shelf generally were between 0.1 and 0.4 knots. Consequently, if Hjølström's values are correct, then fine sediments should be deposited. Since the fine material is not continuously deposited, some mechanism must operate to keep it in suspension and carry it beyond the shelf. Inman (personal communication) has theorized on the possibility of "beat" effects resulting from the impinging of waves on the adjacent shores as a possible mechanism.

Shepard (1941) has discussed some of the possible explanations of nondeposition on the sea floor off southern California and covers the following possibilities: (1) effect of waves, (2) tsunamis (tidal waves), (3) tidal currents, (4) non-tidal currents, and (5) mudflows or submarine landslides.

Effect of Waves

Vening Meinesz (in Kuenen, 1939) reports that submarines are moved considerably by waves at depths of 60 m (200 ft.) during rough weather and he showed how waves approaching shelves have their energy concentrated near the break in slope. Kuenen, therefore, believes this accounts for the common concentration of coarse sediments at the edge of many continental shelves.

Dietz and Menard (1951b), in discussing the origin of continental shelves and slopes, state that "effective erosion" does not exceed 5 fathoms (30 feet). Buffington (1956) takes exception to this view and gives information collected during more than 5,000 dives by Geological Consultants of San Diego. He says that when a diver moves from a depth of about 150 feet to water 90 to 100 feet in depth, there is little or no evidence of disturbance caused by currents or waves. The only exception to this is around headlands and points where bottom currents are occasionally observed. At a depth of 70 to 80 feet there is frequently a noticeable bottom water movement, or surge. This implies that bottom motion extends to a depth of at least 80 feet and perhaps occasionally to more than 200 feet.

Long period waves or storm waves may generate sufficient bottom motion to carry sediments off the shelf. These waves arrive so rarely that they have not been observed in Santa Monica Bay directly. However, bottom photographs taken off Osborn Bank near Catalina Island show a series of large partially destroyed ripple marks. These ripple marks were

possibly formed by long southerly swell in the summer and then reworked by bottom dwelling organisms (see photographs of Emery, 1952, p. 8).

It is noteworthy that sediments are coarser along the edges of the shelves in Santa Monica Bay as shown in Figure 20. It is possible, therefore, that waves (or tidal currents) may concentrate their force along the edge of the shelf and cause this distinct coarsening. However, it is improbable that they result in nondeposition on the shelf, for the area extends from the edge of the shelf near Santa Monica Canyon far to the south and landward.

Possible Effect of Tsunamis

Shepard disregards tsunamis as a cause for nondeposition off the southern California coast. Although one or two tsunamis large enough to do any damage have reached the coast off California in historic time, they are so rare and generally are so reduced in force that they are probably not important in causing nondepositional surfaces in this region.

Effects of Tidal Currents

Strong tidal currents form when large volumes of water flow through a relatively small outlet. Velocities of tidal currents may also increase at the break in the slope or over any rise above the general level of the sea floor. Fleming (1938) found a pronounced increase in the velocity of tidal currents in the Gulf of Panama. Reville and Shepard (1939), on the other hand, found little evidence indicating tides to be an important role in producing nondeposition off southern

California. It must be noted, however, that no detailed studies have been made on the effect of tidal currents in relation to nondeposition off this part of the coast.

A few bottom current measurements were made up to 24 hours duration in various parts of Santa Monica Bay, but no currents were ever recorded which could be directly related to tidal action. It must be concluded, therefore, that tidal currents cannot be the direct cause of the low sedimentation rate on the outer shelf.

Non-tidal Currents

Non-tidal currents include internal waves and large moving eddies with vertical axes. Shepard (1941), utilizing Hjulström's calculations, reports that in all of the localities investigated off southern California, sufficient velocities were found which would transport fine material, and in some gravel could be rolled across the bottom. There were considerable lapses in current velocities in some nondepositional areas which would allow deposition of all sediments except silt and clay. To put the material that had been deposited back into suspension would take high threshold velocities, but the measured velocities (36 cm/sec.) would take sand (.05 - 2.0 mm) back into suspension. Thus, the measurements by Shepard and his associates are sufficient to explain the by-passing of sediments over the nondepositional surfaces, if Hjulström's data applies to the ocean. Shepard (1941, p. 1882-83) questions the importance of these currents because (1) the currents are much weaker than those which are observed in land stream where deposition is gradually building up the stream

bed, and (2) there appears to be no relationship between the observed current velocities and the type of bottom. For example, the strongest current was found on the slope off Palos Verdes Hills where the bottom is covered with mud. Cores showed that mud was deposited to a considerable thickness in several localities where currents were relatively high. In addition, two water samples taken about 3 feet above the bottom during the time of maximum observed currents failed to show any traces of suspended sediment. In both cases, the bottom was covered by silt and fine sand.

Mudflows and Submarine Landslides

Shepard (1941) points out the importance of submarine slides as a cause for nondeposition on some surfaces. While these slides may be important in some localities, such as the head of submarine canyons, the relatively horizontal surface of the outer shelf in Santa Monica Bay probably cannot have significant slumping. Perhaps the exception to this is along the northern boundary of the rock and gravel area where it borders the southern part of Santa Monica Canyon. Parts of this sediment cover may possibly slide periodically off into Santa Monica Canyon. Sliding also takes place along the basin slope, but the study made by Emery and Terry (1956) along the Palos Verdes Slope indicates that considerable thicknesses of sediment can accumulate before the sediment becomes unstable and slides take place.

Relation of Bottom Character to Surface Currents

Shepard and MacDonald (in Revelle and Shepard, 1939, p. 278) report that during a period of calm weather near the head of Santa Monica Canyon, they observed a surface current set to the southeast during the flood tide, whereas there was no appreciable current during the ebb. The same phenomenon was observed during the present survey, but the currents were always weak. Shepard and Revelle state that if the southeast current also exists on the bottom it might carry material to the canyon from the northwest, dumping its load in the canyon so that the water would be relatively free of sediment when it approached the shelf on the south. If such a net current flow exists, there is no reason to believe that the current would drop its load when it reached the canyon. Also, the nondepositional surface extends a considerable distance landward of the Santa Monica Canyon so that if such a current were carrying sediment, it would not cross a depression before reaching the rock and gravel area. Furthermore, the net current flow along the bottom varies through the entire east quadrant and may at times have a seaward set.

Conclusions

The presence of rock outcrops, abundance of phosphorite and gravel, the great number of borings made by pholads and echinoids, and abundance of CaCO_3 are indicative of nondeposition. However, the presence of some fine-grained material indicates that there is some deposition, although it may not be permanently deposited. The origin of non or slight

deposition surfaces is not yet clearly understood, but it is known that in most cases it is due to by-passing of fine sediments by currents or turbulence.

If Hjulström's calculations are approximately correct, then the average velocity of the bottom currents on the outer shelf is not sufficiently strong to cause erosion in the area nor prevent the deposition of fine sediments. This does not mean that strong currents or turbulent action do not, at times occur. There are insufficient data to determine whether the sediment by-passes the region of nondeposition or is deposited and periodically removed by occasional strong turbulence and current action. Since much greater velocities are required to move sediment after it has been deposited than to transport sediment in suspension, it might be reasonable to conclude that the sediment by-passes the area.

Turbulence resulting from internal waves and eddy currents are possibly the cause in this case for nondeposition. However, it is also possible that occasional storm waves, shore wave reflection, and to a minor extent tidal currents may be important.

SOURCE, TRANSPORTATION, AND DEPOSITION OF SEDIMENTS IN SANTA MONICA BAY

Source of Sediments

The principal sedimentological studies undertaken during the course of this survey have been descriptive in nature. As a result, the discussion of sources of sediments is primarily based on published and unpublished data.

Much information on the general nature of the source rocks can be determined from the mineralogy and organic constituents of sediments. For example, the presence of Foraminifera of Miocene or Pliocene age in rocks of Recent age would indicate that the contributing sources included rocks of the older ages. Mineralogically, suites of heavy minerals, including minerals typical of igneous and metamorphic rocks, would indicate the relative importance of these sources.

For the purposes of tabulation of sediment contributions and losses, a general budget has been noted in Table III.

Of the listed contributing items, it is possible to indicate those of least importance. Gains from wind, chemical precipitation, organic production, sewage and industrial wastes, and artificial fill can be regarded as minor. Erosion of submarine rock outcrops is also probably relatively unimportant due to the restricted area of such outcrops in areas of active erosion by waves, and currents. Wave erosion of sea cliffs is not known, but papers by Revelle and Shepard (1939), Grant and Shepard (1940), and Shepard and Grant (1947) would indicate that this contribution is minor. It becomes evident that the major contributing sources are littoral drift and stream-carried sediments. The relative importance of drift versus stream transport is not well-defined at present. The effect of Point Dume as a sediment transport barrier to the north is controversial, for example : Trask (1952), Handin (1951), Trask (1955). At the northern end of the bay the evidence leans toward a southerly movement of sand around the Point Dume area of unknown volume.

TABLE III

SEDIMENT BUDGET FOR SANTA MONICA BAY
(beaches and shelf)

Gained	Lost
<p>Erosion of land within Santa Monica Bay tributary drainage areas; sediments transported to the sea by streams and rain wash.</p> <p>Transport of sediment into the bay by littoral currents from the west and north.</p> <p>Wind transported sediments.</p> <p>Erosion of sea cliffs.</p> <p>Erosion of the sea floor.</p> <p>Chemical precipitates from sea water (phosphorite, etc.).</p> <p>Organic debris (shells and shell fragments).</p> <p>Sewage, industrial, and shipping wastes.</p> <p>Artificial fill; artificial nourishment of beaches, dumping of sediments along the coast for highway construction, etc.</p>	<p>Landward transport of beach sediment.</p> <p>Transport of fine sediment beyond the shelf by currents and waves.</p> <p>Periodic slumping or submarine landslides carrying sediments on the shelf, basin slope and in the submarine canyons seaward into deeper water.</p>

The movement of sand along the central bayshore has been the subject of several investigations in past years. As a result of these studies, it seems probable that the bay acts as a trap for most of the entering sedimentary material coarser than fine silt and clay. Such a conclusion indicates a negligible transport around Palos Verdes Hills coast. This is likely true because of (1) the probability that most of the sediments carried to the south by littoral currents are trapped by the Redondo breakwater or are carried into Santa Monica-San Pedro Basin through the canyon; (2) observations by the U. S. Army, Corps of Engineers (1955) indicate that there is a pre-dominant downcoast drift of sediment to Redondo, and a net up-coast drift between Clifton and Rocky Point; (3) Johnson (1940) noted that between 1939 and 1940, 370,000 cubic yards of sediment accumulated on the south side of the Redondo breakwater, but very little on the north side. He postulated a southeast source for the sand drift. It may also be, however, that conditions are such that the sand is by-passed around the breakwater and deposited on the southern side, thus originating from the north; (4) bottom samples close to shore around the Palos Verdes coast indicates rocky bottom and little or no sediment cover. Only small pocket beaches of locally derived composition occur along this rugged section of the coast. Most of the shore consists of rock platforms and cobble beaches; (5) wave refraction diagrams in the southern part of Santa Monica Bay show that a northward drift near Rocky Point would be accomplished with greater ease than a southeast drift around the Palos Verdes Hills; and (6) more or less permanent rip currents occur in the

vicinity of Redondo and Clifton and indicate a convergence of littoral currents in this area.

Therefore, the sediment within the bay probably represents all sediment contributed by local stream drainage plus littoral drift contributions from the north minus the loss of fine grained sediments to the offshore area, and the loss of coarser sediment down the submarine canyons to the basins. Some losses, although very minor, also can be charged to wind drift from the beaches inland.

Drainage Tributary to Santa Monica Bay

Figure 3 shows the boundaries of the drainage areas and the streams bordering Santa Monica Bay. Table IV lists the areas and characteristics of the various zones. It can be seen that the Santa Monica Mountains comprise the major element. The area southeast of Santa Monica Harbor is mainly coastal plain, while that northwest of the harbor is primarily mountainous.

Inland from Malibu several water supply dams have been built which cut off much of the coarser sediment from the bay. As this watershed alone constitutes 58% of the drainage in this area, the remaining smaller watersheds have been lumped together.

Rate of Sedimentation

It is difficult to calculate the rate of sedimentation in Santa Monica Bay for several reasons. A number of the problems concerned with source areas are obvious. The volumes

TABLE IV

DRAINAGE AREAS OF THE SANTA MONICA BAY AREA

1. Total Area:

Mountainous region (elevations to 2,500')-----	217 sq. mi.
Coastal plain region (below 500')-----	120
Areas adjacent to coast without well developed drainage-----	<u>10</u>
Total-----	347 sq. mi.

2. Area Southeast of Santa Monica Harbor:

Ballona Creek Watershed-----	131 sq. mi.
Kenter Canyon Watershed-----	10
Sand Dunes and northern Palos Verdes Hills-----	<u>19</u>
Total-----	160 sq. mi.

3. Area Northwest of Santa Monica Harbor:

Malibu Creek Watershed-----	109 sq. mi.
All other smaller watersheds-----	<u>78</u>
Total-----	187 sq. mi.

of sediments calculated by various authors are based upon conditions existing at the present time, but the volume has varied greatly. Numerous natural and artificial changes in the drainage areas have taken place within historic time which have greatly altered the sedimentary regime of Santa Monica Bay. The following is a partial list of some of the most significant changes:

1. Construction of storm drains and debris basins which have greatly altered the former natural drainage and as a consequence, the amount of detritus reaching the bay.

2. Construction of the coast highway which has prevented cliff erosion. On the other hand, large quantities of sediment have been dumped along the coast in order to widen the highway. Davidson (in Cong. Docs., 1897) reported that in 1872 when traveling in a wagon along the northern part of Santa Monica Bay, the cliffs came so close to the shore and the canyons were so steep, that he could only pass this region at low tide. As proof of former erosion of the cliffs in this region, Davidson says:

"At Point Dume a very fierce westerly wind sprang up and retarded my operations so that in returning to Santa Monica I was on the beach through two low waters. I found the beach torn away along the whole shore line, and met with rocky obstructions which in some cases had been wholly uncovered by the washing away of the sands. As we approached Santa Monica the evidences of this destructive action became more and more marked, and for the last 2 or 3 miles the beach was torn away from 10 to 12 feet in depth."

3. Urban development has stabilized erosion over most of the coastal plain and parts of the Santa Monica Mountains.

4. Widening of beaches by artificial nourishment, construction of breakwaters, and by the use of groins and jetties. The construction of coastal engineering structures above Pt. Dume has also cut off large amounts of sediments that may have reached the bay in the past.

5. Beach erosion by the construction of breakwaters, i.e., downcoast from Santa Monica and Redondo breakwaters.

6. Stream piracy of the westward flowing Los Angeles River, and also the changes made in Ballona Creek outlet.

7. Construction of reservoirs which have greatly reduced the quantity of sediments reaching the bay. At the present time only very fine material is washed over the dams and reach the sea. The following are the most important

reservoirs and the date of their construction; all are in the Malibu Creek watershed: Rindge Reservoir (1925); Craggs Lake (1913); Malibu Lake (1923); Lake Eleanor (1881); Lake Sherwood (1904).

Other questions arising when calculating the rate of sedimentation in Santa Monica Bay (specifically the shelf) are the following: (1) How far are the sediments transported before they are deposited? (2) Are the coarse sediments deposited close to shore and most of the fine material carried great distances, i.e., beyond the shelf, before being deposited? (3) How much sediment is carried seaward along the floor of the submarine canyons, especially Redondo Canyon? (4) How much sediment is deposited along steep slopes or at the head of the canyons and later slumps into deeper water? (5) What volume of sediments is winnowed from the shelf and carried beyond the shelf before being redeposited? (6) What effect do animals have on breaking down sediments thereby producing finer material that may be winnowed away?

Theoretically there should be an even gradation from coarse to fine sediments in a seaward direction. In general, this theory applies to Santa Monica Bay although there are several parts of the bay that appear anomalous. Some of the abnormal regions are due to quiet water close to shore (Redondo Canyon) which allows the accumulation of fine detritus. One of the major causes of the peculiar sediment distribution undoubtedly results from the superposition of present day sedimentation on top of a surface formed largely in the geologic past. For example, the rock and gravel area on the outer shelf is believed to have formed in late Pleistocene or early Recent time. Thus,

a general seaward decrease in texture exists, but it is modified by (1) the presence of sediments deposited in the geologic past, and (2) submarine topography which in part causes deviations in the sediment distribution.

Probably most of the clay and a large portion of the silt originating within the distributary drainage area is carried beyond the shelf and deposited in the offshore basins. It is likely that bottom scavengers break up sediments into smaller particles, but there are no quantitative data on this process. It is probable, however, that beach sand does not become appreciably broken down by transport along the coast by littoral drifting (Mason, 1942).

Since littoral drift along most of the shore is southeastward, and meets northward drifting sand at Redondo, some of the sand must go seaward - presumably out through Redondo Canyon. After the construction of Redondo breakwater, much of the southward drifting sand was trapped by this structure. Prior to the construction of the breakwater, however, a large amount of sand may have been lost through the canyon. According to Mr. William Herron, Army Corps of Engineers (oral communication), a considerable quantity of sand is lost seaward between Santa Monica and Redondo, and at the present time it is possibly as much as 150,000 cubic yards per year.

Although sediments may accumulate on slopes and later slide off into deep water, this does not seriously effect calculations on the rate of sedimentation on the shelf. More important, however, is the amount of sediments deposited and later resuspended and carried in a seaward direction. The more or less continuous

redistribution of sediments makes it difficult to determine how fast sediments accumulate at any particular point. Sediment traps have been constructed by Emery and placed on the sea floor off southern California. Apparently, most of the sediment collected in the traps is the result of the movement of sediment along the bottom. A number of investigations in various parts of the world have shown that in relatively shallow water, where the investigations were made, there is an almost continuous change in the texture of the sediments. Thus, the median diameter, or per cent sand, silt, and clay vary greatly over relatively short periods of time. It can only be assumed that sediment movement along the bottom is zero at any particular time when the calculated rate of sedimentation is made; or in other words, the sediments are in a "steady state condition".

Assuming that 80% of the sediments are deposited within 8 miles of shore or over an area of 200 square miles, and the estimated volume of sediments is 478,000 to 650,000, then the rate of sedimentation would be between 0.02 and 0.03 inches per year. Thus, even if the calculations are off by factors of 2 or 3, the overall rate of sedimentation is slow at the present time.

While it is not possible to quantitatively estimate the rate of sedimentation over a long period of geologic time, a few conclusions can be reached on the relative rate of sedimentation and to changes in the depositional history of the bay.

Natural or artificial changes in the tributary drainage areas and changes resulting from other works of man, are indirect evidence that the sedimentation in Santa Monica Bay has varied. In addition, it can easily be shown that pronounced changes in sedimentation have taken place by examination of the sediments in the bay.

There are a large number of cores, jettings, and borings taken in various parts of the bay and on land close to shore. They show that numerous textural changes occur in a short vertical section of any random core or jetting. Thus, there are distinct beds or laminations of gravel, silt, sand, clay, silt and gravel, beds of shells, and even layers of vegetation. Although cores that are close together may show some correlation, there is in general a poor core to core correlation. The pronounced alterations in texture can only be explained by changes in the competency of the transporting agents(waves and currents), and to variations in the supply of detritus supplied to the bay, and/or to alternate cutting and filling of the nearshore shelf sediment surface.

Rain falling in the tributary drainage areas can have several different effects upon the supply of detritus to the bay, depending upon the amount and distribution of the precipitation. If the rainfall is small, only silt and clay will be brought to the bay. If there is slightly more precipitation, considerable amounts of coarser sediments, especially material of about fine sand size may be washed to the bay. If a flash flood occurs, material ranging in size from clay to boulders

may be carried to the sea. If there have been several years of only small rains, the stream may have built up to a thick deposit of sediment in its channel. Then when a flash flood occurred the sediment in the channel may move out into the bay as a plug of sediment (Revelle and Shepard, 1939). Under such circumstances a great heterogeneous mass of unsorted fragments will be deposited in the bay. Waves and currents may then redistribute the sediment over a larger area.

The presence of considerable quantities of coarse sediments, especially gravel, over a large part of the bay probably indicates that sedimentation in the past was faster than now and the source of sediments was much greater. The volume of sediment brought to the bay during periodic storms must have been great. Cores taken far out on the shelf generally do not show many distinct beds of gravel, but gravel is widely distributed over most of the bay as was shown in Hayward grab samples. This distribution may be the result of extensive reworking by marine processes after initial deposition.

Distinct and correlative beds of clay are conspicuous at the site of the Santa Monica breakwater and farther to the south. Clay can only be deposited in quiet waters which are not disturbed appreciably by waves or currents which would wash away the clay, nor can there be a large supply of coarse detritus. The thick deposits of clay are therefore difficult to explain unless it is assumed that one or more offshore bars allowed fine grained sediments and vegetation to accumulate in the quiet water behind the bars. These hypothetical offshore bars migrating landward might have been the major source of

sand in the El Segundo Sand Hills. Several geologists who have studied the sand dunes have concluded that they might be the result of offshore bar migration.

The above discussion is sufficient to indicate that considerable changes in the depositional history of the bay have taken place, and that on the whole, the rate has decreased in historic time. The changes are attributed largely to alterations in the tributary drainage areas and to the work of man, but climatic changes may in part be responsible for the decrease in the rate of deposition.

Deposition in the Past Two Decades

A comparison of Shepard and MacDonald's samples with those collected by the Hancock Foundation reveal that nearly all of the samples collected in the 1934-38 period or earlier were coarser-grained than those obtained approximately 22 years later. There are several possible explanations for this: (1) Shepard and MacDonald used a pipe dredge to collect their samples and some of the finer sediments may have washed out during the dredging operation. Dr. Shepard (personal communication) reports that a piece of cloth was used over one end of the dredge, and that once the dredge was full little washing took place. (2) The mechanical analyses made by both collectors were different. The samples collected by Shepard and MacDonald and the Hancock Foundation used standard sedimentary techniques. However, the Emery settling tube was used to analyze the coarse sediments at Hancock Foundation, whereas the earlier samples were analyzed using screens. The

settling tube technique is comparable with analyses made by screens, so that no difference should have resulted in the sedimentary parameters from these practices. (3) There has been an increase in the percentage of fine sediments, especially silt and clay, since Shepard and MacDonald collected their samples. It is known that the volume of sediment reaching the bay has decreased in historic time. It might be reasonable to conclude that there has also been a decrease in grain size. In other continental shelves and submarine regions where sediments were collected again after a lapse of time there frequently are pronounced changes in texture. In some areas where sediments have been collected only a month apart the various sediment parameters may differ so greatly that there is little similarity to be seen.

Although an attempt was made to quantitatively measure the rate of sedimentation by comparing Shepard and MacDonald's samples with those collected by the Hancock Foundation (Table V), the results were inconclusive because it was difficult to accurately estimate the sediment thickness represented by the samples. The only conclusion that can be drawn from the two sets of samples is that most of Santa Monica Shelf appears to be accumulating material finer than prior to about 1934.

TABLE V

COMPARATIVE RESULTS OF TWO SETS OF SEDIMENT SAMPLES
FROM SANTA MONICA BAY

Shepard and MacDonald				Present Survey			
Station No.	Median Diameter	% Sand	% Silt & Clay	Station No.	Median Diameter	% Sand	% Silt & Clay
124*	0.063 mm	50.4	49.6	3361**	0.030 mm	75.9	23.9
166	0.074	62.8	37.2	3103	0.022	17.5	82.5
107	2.060	97.6	2.4	3165	0.033	36.1	63.9
422	0.101	97.7	2.3	3350	0.062	50.0	50.0
332	0.270	92.5	7.5	3393	0.114	75.4	24.6
319	0.072	74.5	25.5	3244	0.058	44.6	55.4
431	0.067	58.6	41.4	3181	0.063	50.2	49.8
117	0.107	78.6	21.4	3226	0.090	65.0	35.0
F	.077	84.1	15.9	3410	0.065	58.4	41.6

* For location see Shepard and MacDonald (1938).

** For location see Appendix.

Other changes appear to have taken place since 1934-38 in the bottom sediment distribution. The most outstanding is the lack of evidence of a rocky area reported by Shepard and MacDonald to be one to two miles offshore between Playa del Rey and Manhattan Beach. Shepard and MacDonald stated that part of their data was based upon reports by fishermen and also bottom notations by the U. S. Coast and Geodetic Survey. It is possible that this region was delineated largely on the basis of scattered notations of hard bottom that actually may have been gravel, since it has been found that gravel is widespread nearshore. At that time extensive patches of coarse gravel perhaps were exposed at the surface and these were taken to indicate rock. Nevertheless, there is no indication of rock bottom in this region so far as could be determined during the present survey, and either no rock exists here, or it has been covered by a considerable thickness of sediment since the earlier report was made. The submarine topography gives no clue, for the micro-relief in this region is very smooth.

Submarine Landslides and Slumping

While the vertical changes in lithology over most of the shelf are explained by variations in the quantity and quality of sediments deposited and also in part to oceanographic conditions (waves, currents, etc.), the frequent textural changes in cores taken in submarine canyons are due largely to an additional factor - submarine landslides or slumping.

Sediments accumulating on a slope are unstable and the stability of the deposit in general depends upon; (1) the size and sorting of the sediment, (2) water content, (3) the degree of compaction, and (4) the angle of the slope. Loose, fine-grained sediment having a high water content and accumulating on a steep slope is unstable and eventually slides off the slope into deeper water.

Shepard has shown that slumping and submarine landslides are common, especially when the canyons are close to shore where there is an abundant supply of sediment. No quantitative data exist on the periodicity of slumping, but it is likely that the sediments are unstable on the slopes of submarine canyons, and that slumping takes place fairly often. A detailed study of a slope off Palos Verdes Hills indicated that appreciable quantities of sediments may accumulate on a slope before slumping takes place, but evidence was presented that indicated slumping very probably did occur (Emery and Terry, 1956). Benest (1899) pointed out the difficulties that resulted from placing telephone cables across submarine canyons, and the difficulty was not remedied until the cables were placed on the shelf well above the head of the submarine canyons.

The cores taken in Santa Monica and Redondo canyons indicate that slumping and sliding probably takes place, particularly in Santa Monica Canyon.

GEOLOGICAL STRUCTURE OF SANTA MONICA BAY

Seismology

The seismological data used in the preparation of Figure 34 have been taken from the California Institute of Technology, Seismological Laboratory, Bulletin on Local Shocks. The four types of "Quality" shown in the legend of the diagram refer to the accuracy in location of the epicenter. "Magnitude" ("M" on the chart) refers to the relative movement of the ground using Richter's scale (Gutenberg and Richter, 1942). The magnitudes range from 0 to about $8\frac{1}{2}$, the latter being the largest shocks recorded anywhere in the world. A brief comparison of magnitudes and their approximate extent in damage are listed below.

<u>Magnitude</u>	<u>Effects</u>
0	Slight shock - probably imperceptible to humans.
1	Slight shock - possibly felt near epicenter.
2	Very small shock - felt slightly over a small area of a few miles in radius.
3	Small shock - felt sharply over a small area, but incapable of causing any but insignificant damage.
4	Moderate shock - may cause considerable minor damage near the epicenter; felt to a distance of about 45 miles.
5	Minor shock - may be destructive near the epicenter, with damage over a larger area; felt to a distance of about 125 miles.
6	Major shock - a strong destructive earthquake.
7 & 8	Progressively stronger destructive earthquakes.

The Long Beach earthquake of March 10, 1933, had a magnitude of about 6.3. The last series of major earthquakes in southern California of comparable magnitude were the Kern County shocks of July and August 1952, which had magnitudes of 7.6 to 7.7.

Figure 34. Distribution of epicenters in Santa Monica Bay.

DISTRIBUTION OF EPICENTERS

BOTTOM CONTOURS IN FEET
● EARTHQUAKE EPICENTERS

Q	M
A - SPECIALLY INVESTIGATED - NONE	
B - PROBABLY WITHIN 3 MI. - 3.2	
C - PROBABLY WITHIN 10 MI. - 3.2	
D - VERY ROUGH	- 3.2

All shocks, including aftershocks, from 1934 to April 1955, are shown in Figure 34. The shocks are located to the nearest minute of latitude and longitude, and the qualities on the chart are shown by the varying style of lettering for the magnitude number.

It is difficult to make definite conclusions about the relationship of earthquakes to the geological structure of Santa Monica Bay for several reasons; (1) most of the shocks are poorly located (2) statistical studies of the earthquakes are not possible due to the inaccuracies in location, and (3) in most cases, earthquakes do not originate at the surface, but at a depth of several miles.

Most earthquakes in the California region are associated with faulting. Numerous large faults and countless small faults exist in the vicinity of Santa Monica Bay. The largest and most important fault in the region is the Newport-Inglewood fault zone, which originates in the Santa Monica Mountains near Beverly Hills and continues more or less uninterrupted to Huntington Beach where it goes out to sea. The faulting in this zone is not one major fault, but is composed of numerous short overlapping faults. Other fractures that may be of importance to the geological history of Santa Monica Bay are the Malibu fault and the San Pedro or Palos Verdes fault zone. All of these have been discussed to some extent earlier in this report.

The Palos Verdes fault zone is known to leave the coast in the vicinity of Redondo Beach, but just what happens to the fault after it reaches the bay is somewhat obscure. Some

geologists think that the fault turns west or southwestward down the axis of Redondo Canyon. However, there seems to be more evidence that it may continue in a northwestward direction. The following information perhaps supports this theory: (1) numerous oil and gas seeps are found at the head of Redondo Canyon and farther to the northwest, (2) the large grouping of earthquake epicenters in the vicinity of Santa Monica Canyon (lat. $32^{\circ}57'$, long. $118^{\circ}38'$), (3) the general pattern of the submarine topography suggests that faulting perhaps has played a role in its origin, and (4) the discovery of schist on the outer shelf appears to correlate with the schist in Palos Verdes Hills and the basement rock in the Los Angeles Basin.

Clements and Emery (1946) plotted epicenters for the offshore area in southern California and found them to be grouped along straight steep slopes which they believed to be of fault origin. No such groupings occur in Santa Monica Bay so that the relatively steep slopes are probably due to other factors, or the faulting that may have been important in the formation of the slopes is now inactive. It is noted that Redondo Canyon has the appearance of fault control since it is deep, has steep walls, and has a straight longitudinal profile. However, if faulting played an important part in its formation, it must have been in the geological past since there is no seismological evidence of faulting at the present time.

The only earthquake in Santa Monica Bay that has received special study occurred on August 30, 1930 (Gutenberg, Richter, and Wood, 1932) and was located in the area where a large

number of shocks are reported in the northern part of the bay.* For more than three years prior to this shock there were numerous small quakes which were felt in the beach cities. The main shock had a magnitude of 5 followed by 16 immediate aftershocks. Ioseismal lines (lines of equal magnitude) indicate that the shock was felt more than a hundred miles away. It was calculated that the shock originated at a depth of 6 to 9 miles below the earth's crust in bedrock, probably granite.

Thickness of Overburden

Thicknesses of unconsolidated sediment in several parts of the bay are shown in Figure 35. Thicknesses of less than 10 feet are found in the rock and gravel area on the outer shelf, off the Malibu and Palos Verdes coast. U. S. Coast and Geodetic Survey charts and a chart prepared by Johnson (1940) also show rock off the coast of Malibu. The overburden increases eastward from the outer shelf, and reaches a thickness of 500 feet within one mile of the rock and gravel area.

The scattered patches shown in Figure 36 are geophysical anomalies and probably are due to irratic or scattered patches of gravel, except some of the nearshore ones which may be rock a short distance below the surface.

*This shock has not been shown on Figure 34 because it took place before 1934. Prior to 1934, earthquakes were not systematically recorded. They were largely "eye-witness" accounts and have little scientific value.

Figure 35. Probable thickness of overburden in Santa Monica Bay.

Figure 36. Areas of anomalous seismic data in Santa Monica Bay.

Structure

Figure 37 is a generalized diagram showing the lithology of the upper few hundred feet of sediments near the shore. The impervious clay cap in the upper part of the San Pedro formation is believed by ground water geologists to extend only to the shore in the region shown by the diagram. However, a similar clay cap was found at the site of the Santa Monica breakwater and also along the old Hyperion outfall course. In the latter case, however, the clay in the cores may or may not be the same clay cap identified on land, but at the Santa Monica breakwater the clay cap was found in every core, at or very close to the surface of the sea floor. The "Silverado zone" of the San Pedro formation probably extends only 2 to 3 miles offshore, but the other formations lower in the geologic section may extend far out onto the shelf.

Two geologic formations in the Los Angeles region may be correlative with the schist cropping out on the shelf; the Catalina schist and the San Onofre breccia. The San Onofre breccia is Middle Miocene in age; the Catalina schist may be pre-Cambrian or Mesozoic (Jurassic?). The Catalina schist underlies almost all of the Los Angeles region and crops out in the Palos Verdes Hills. The San Onofre breccia was formed by the erosion of the underlying Catalina schist, and consists of angular blocks up to 10 feet in diameter (Woodford, et al., 1954, p. 71). Even though there is a significant difference in the age between the Catalina schist and the San Onofre breccia, it is difficult to assign a definite age to the schist fragments found in Santa Monica Bay.

Figure 37. Geologic cross-sections in the Santa Monica Bay area.

STATUTE MILES

OCEAN PARK PLAIN

+400'

+200'

BALLONA GAP

0'

-200'

-400'

EL SEGUNDO SAND HILLS

U. Pleistocene

San Pedro fm

base of upper Pleistocene

silverado zone

Pico fm.

PALOS VERDES HILLS

+400'

+200'

0'

-200'

-400'

Perhaps only a small number of schist fragments have been found in the region because the original outcrop had been covered by Miocene and later sedimentary deposits and only recently was partially uncovered by erosion. Since Pliocene age Foraminifera have been found both to the east and west of the rock areas and only Foraminifera of the Miocene and Recent periods in the rocky area, perhaps erosion in post-Miocene time carried sediments from the topographically higher rocky area leaving only Miocene and Recent age rocks where rock is now exposed. If this is true, then the rock and gravel area has suffered deep erosion, including deposits of the Miocene, the Pliocene, and perhaps Quaternary periods. If deep denudation took place in this part of the bay, the gravel might be a residual deposit brought about by erosion and winnowing of fine material. This process is similar to the accumulation of "lag gravels" in desert regions in which the wind removes fine-material and leaves a residual deposit of coarse gravel.

In the El Segundo oil field, the Franciscan (?) or Catalina schist is overlain by a schist conglomerate and nodular shale at a depth of 7,000 feet below sea level. The conglomerate in this oil field was formed by the weathering of the underlying Catalina schist. It is conceivable, therefore, that the schist fragments and the gravel on the outer shelf have a similar origin. A possible argument against this theory is the almost complete lack of schist fragments or gravel composed of schist elsewhere in the region. In addition, the gravel is not restricted to the rock and gravel region on the outer shelf, but is found in scattered patches over the entire bay.

The schist cropping out on the sea floor may correlate with the Catalina schist assuming that the equivalent to the San Onofre breccia never was deposited on top of the Catalina schist in this area or that the schist breccia (or conglomerate) has been almost completely removed by erosion. Since the schist outcrop on the sea floor is a topographic high now, and probably was a high area when it was buried during Miocene time, it may be reasonable to assume that no significant quantities of fragments of schist could accumulate. Fragments of schist that might have broken off during weathering prior to burial would have accumulated in low areas, but a few fragments of schist might have been incorporated into the overlying shale.

Although the difference in geologic time between the Catalina schist and the San Onofre is very great, sedimentary rocks of Miocene and more recent ages frequently rest directly on the basement rock. Therefore, whether the schist dredged from the outer shelf is basement rock or its weathering product is not too important.

Rocks in the El Segundo oil field located approximately one mile east of Hyperion range in age from Recent to Jurassic (?). Pliocene and post-Pliocene age rocks having an aggregate thickness of 5,700 feet are composed largely of alternating sands and shales, except the lower 450 feet which is composed of shales alone. Sediments of Pliocene age are underlain conformably by 1,300 to 2,000 feet of Miocene shales. The basal section of the Miocene is made up of a nodular shale, and a schist conglomerate. The Catalina or Franciscan (?) schist of Jurassic (?) age

unconformably underlies Miocene age sediments. The stratigraphic section is shown diagrammatically in Figure 37 in which two possible interpretations of the structure between the El Segundo oil field and the outer shelf are presented.

The fossiliferous shales and mudstones dredged from the rock and gravel area on the outer shelf are Upper Miocene in age and correlate with the shales in the El Segundo oil field. The schist recovered on the outer shelf is, therefore, correlative with either the schist conglomerate or with the basement schist. The structure between the outer shelf and the shore can be explained by one of two theoretical structures or perhaps by a combination of them. They are: (1) A very gentle dipping syncline or trough exists with rocks of Upper Miocene age and possibly the schist basement exposed on the western limb of the syncline, and Pliocene age rocks in the central part of the bay are covered by sediments of the Quaternary age. Sediments derived from this island and from land to the east eventually filled the trough. (2) The Palos Verdes fault zone extends northwestward from the Palos Verdes Hills and has uplifted the outer shelf several thousand feet. Rocks younger than Miocene have subsequently been eroded away leaving only Miocene and perhaps basement rocks on the outer shelf. The Palos Verdes fault dips steeply to the northeast along the north side of the hills, but it would have to have a relatively low dip to account for the changes in the thicknesses in overburden on the shelf. It is noteworthy that Corey (1954) and Woodford, et al. (1954) show a continuation of the Palos Verdes fault across the Santa Monica shelf.

It would appear, therefore, that on the basis of available data there is a considerable thickness of sediment between the coast which probably becomes thinner towards the outer shelf as shown in Figure 38. Although sedimentary rocks of various ages may be covered by only a thin veneer of Recent sediments in the inner shelf region, it is highly improbable that basement occurs at or near the surface anywhere in this area. A detailed study of fathograms taken over most of the shelf indicated that most of the inner shelf out to a depth of about 170 to 180 feet is a depositional plain. This suggests that deposition of sediments has covered a large portion of rock of Pleistocene age and older which possibly at one time were exposed at the surface. However, some areas, such as the regions where red sand occurs, and at the head of Santa Monica Canyon, relic sediments have not been covered. Since some of these relic sediments do not have any discernable relief, they must be at equilibrium with the present depositional surface, and as sediments are spread evenly over the entire region they will be covered. This assumes, of course, that most of the shelf is undergoing aggradation, and there appears reason to believe that this may be partly true.

No definite statements can be made for most of the other parts of the bay since data are lacking. Nothing is known concerning the age of the rocks beyond the shelf break, but a large variety of rocks have been dredged from the submarine canyons by Emery and Shepard (1945). A few of the rocks had a possible age of Pliocene, but it appears as if the bulk of the rocks should be dated as Miocene. No schist has been found in the canyons. This imposes a very interesting question: If the

Figure 38. Hypothetical cross-section across Santa Monica Bay Shelf.

schist on the outer shelf is basement or near basement (San Onofre), then all rocks below the schist must be basement also; which means that all rocks found in the deeper parts of the bay should be composed of schist or at least basement rock of some kind. Thus, if schist occurs on the outer shelf at the surface, then only schist or basement rock should be found in the Santa Monica Canyon. This is not the case since most of the rocks dredged from the Santa Monica Canyon were Miocene in age. One way to explain this anomalous problem is by assuming that an east-west trending fault separates the rock and gravel area on the outer shelf from the region north of the submarine canyon. Such a fault would tilt the region north of the axis of the submarine canyon downward, and uplift the outer shelf. In this manner, Miocene and post-Pliocene rocks could still be present in the canyon, but have been largely removed by erosion on the outer shelf. Another alternative is to assume that the schist dredged from the outer shelf is not in place. Third, the schist and gravel area of the outer shelf may represent an eroded dome-like structure.

Poland, et al. (1948) mentions that the Ballona escarpment along the southern boundary of the Ballona Creek has characteristics which suggest faulting. For example, the escarpment is more or less straight over most of its length, but more important is the fact that the gravels in the old stream channel are thicker on the south side. The thickening to the south can be explained by tilting of the land area to the south and by assuming an east-west trending fault at the southern boundary of the stream channel. It is possible that the faulting and

tilting proposed by Poland, et al. also is responsible for the tilting of the northern flank of Santa Monica Canyon.

A large percentage of submarine canyons have streams or former streams entering into the head of the canyon. No problem is involved in the origin of Santa Monica Canyon since Ballona Creek is known to have flowed into the bay until 1825, and probably flowed directly into the head of Santa Monica Canyon when sea level was lower. Redondo Canyon, on the other hand, has no historic, topographic, nor sedimentary record of a former stream landward of the canyon. The only evidence known which indicates that the region at the head of Redondo Canyon may have had a stream is the existence of marsh or lagoonal deposits at about sea level one-half mile inland.

Although faulting may have played some role in the control of Redondo Canyon, some additional agent is necessary to cut the gorge. Two theories which are most commonly argued for the origin of submarine canyons are; (1) subaerial erosion by streams, and (2) erosion by turbidity currents. A detailed discussion of these theories and others are unnecessary here; however, it is necessary to briefly state the turbidity current hypothesis. Sediments accumulating on the shelf or in the upper reaches of the submarine canyon periodically slump or slide into deeper water. The material that slumps has a very high water content and travels at a high velocity which is assumed to have the power to erode the bottom and walls of the canyons.

It is obvious that there is no apparent abundant source of sediments which could form turbidity currents; therefore, both

theories appear to be inadequate to explain the origin of Redondo Canyon. Two possibilities are proposed for the origin of this canyon: (1) The two large tributaries on the north wall of the canyon are the result of erosion by one or more tributaries flowing from Ballona Creek. Thus, Ballona Creek was responsible for erosion of Redondo Canyon as well as Santa Monica Canyon. Perhaps the stream actually flowed out the head of the canyon, but this is difficult to prove. Redondo Canyon then could migrate landward by headward erosion. (2) A stream flowed to the north of Palos Verdes Hills, but is so old that all evidence of its existence has been obliterated by later reworking and deposition of sediments. The region might have been a wide flood plain close to sea level and therefore could supply large quantities of sediments for turbidity currents - if this was the origin of the canyon.

A tongue of sediments extending from the western tributary on the north side of Redondo Canyon towards Ballona Creek is evident on most of the bottom sediment charts. This suggests that the former stream channel may still be evident as shown by the superficial sediment deposit, or present oceanographic conditions have an influence on the distribution of sediments, and for some reason are related to the old tributary.

SUMMARY

The Geologic and Geographic Setting of
Santa Monica Bay

Santa Monica Bay is bordered on the north by a mountain range that has been uplifted along east-west trending faults. On the southwest, the Palos Verdes Hills have been elevated during relatively recent time. The north side of the hills is separated from the Los Angeles Basin by a fault trending in a northwest direction. This fault probably extends into Santa Monica Bay and has played an important role in its structural history. The relief in the Los Angeles Basin was formed largely in Late Pleistocene and early Recent geologic time and the tectonic forces responsible for deformation probably have also affected the submarine geology of the bay. Thus, the structure of Santa Monica Bay is more related to forces active in the Los Angeles Basin and Palos Verdes Hills than to tectonic activity in the Santa Monica Mountains. Earthquakes on land and in the bay, and other lines of evidence indicate that deformation is still taking place.

The major drainage into the bay is from the southern slopes of the Santa Monica Mountains, while there is little or no drainage from the area south of the city of Santa Monica. Prior to 1825 Ballona Creek drained a large inland area, but since that date only a minor amount of material has entered the bay through the Ballona Creek outlet. A variable amount of sand comes into the bay around Point Dume, but probably no material finer than beach sand comes from this source.

Submarine Topography

The major submarine topographic features in Santa Monica Bay are the shelf, Redondo and Santa Monica Canyons, the Basin Slope, and Santa Monica Basin.

The shelf is generally smooth and grades gently from shore to a depth of approximately 270 feet. The surface shows several distinct types of minor "micro-relief". Nearshore there are bars and troughs; farther offshore are areas of smooth topography with no micro-relief, and near its edges the shelf shows variable micro-relief with small terraces and notches locally present. On the portion of the shelf projecting between the two submarine canyons irregular micro-relief consists of low mounds and ridges and corresponds to the major rock and gravel area.

The two submarine canyons are incised into the shelf and create the lobate outer projection of the shelf. These canyons are V-shaped with relatively steep walls. Redondo Canyon is cut through the shelf to within a few hundred feet of shore, whereas Santa Monica Canyon has its head about $3\frac{1}{2}$ miles from shore.

At the edge of the shelf the gradient increases markedly and the slope grades into an offshore basin. These slopes appear to be smooth, but a few notches or terraces are known to occur.

The floor of Santa Monica Basin, starting at a depth of approximately 2,700 feet is relatively smooth, but slopes slightly in a seaward direction.

Unconsolidated Bottom Materials

Sediments are classified on the basis of a three-component system of gravel, sand, and silt content, and are subdivided further on the basis of color. Although the sediments represent a gradual progression from sand nearshore to silts offshore, this progressive change is disrupted by areas of coarse sediment. These coarse deposits are composed of relic sediments, organic debris, and authigenic minerals.

The highest percentages of sand are in the nearshore regions, at the head of Santa Monica Canyon, and in some isolated patches on the outer portions of the shelf. Sand is the main sediment component in the bay. The greatest percentages of silt are along the basin slope and in the submarine canyons. Clay rarely exceeds 20 per cent of the sediment except in parts of the submarine canyons and in the Santa Monica Basin.

All deposits have fine-grained sediment associated with them, indicating that fine material is deposited to some extent in all parts of the bay. Intermittent removal of fine-grained sediment may be the most important factor in preserving the relic deposits.

An examination of the sand fractions of the sediment resulted in the establishment of six distinct types; (1) fine quartz-feldspar sand, (2) rock fragment sand, (3) glauconite sand, (4) phosphorite-glauconite-shell sand, (5) shell sand, and (6) red sand.

Fine quartz-feldspar sand covers most of the shelf, and is the terrigenous detrital material being deposited in the bay at the present time.

Rock fragment sand is the coarse fraction of nearshore and offshore sands and silty sands, and represents a relic sediment that was deposited during lower stands of sea level.

Glaucinite sand is the coarse component on the basin slope circling the outer shelf, on the seaward portion of the shelf off the Malibu coast, and near the tip of the shelf south of Redondo Canyon.

Phosphorite-glaucinite-shell sand is the coarse fraction of the sands and gravels, and of the finer sediments of the outer shelf projection between the two submarine canyons.

Shell sand occurs as the coarse component of some of the fine-grained sediments on the basin slopes.

Red sand is in scattered areas in the nearshore region. This material is a relic beach or dune deposit formed at lower stands of the sea, and has not yet been covered by Recent deposition.

The distribution of median diameters indicates that the grain size of the sediments decreases in an offshore direction. The decrease is modified by coarse relic material, authigenic minerals, and organic fragments occurring offshore. Also, slumping or sliding of sediment on the slopes tends to modify this distribution pattern.

The distribution of coarse sediments in patches throughout the bay tends to indicate that there are localized areas of non-deposition, or areas of intermittent deposition.

The distribution of median diameters indicates that there is continuous marine deposition taking place nearshore between Santa Monica and Redondo Beach, and on the shelf off the Malibu

coast. The sediments in these regions are affected by currents and waves at the present time, and as a consequence reflect present environmental conditions.

Most of the shelf sediments are well-sorted. Moderately- and poorly-sorted sediments on the basin slope and on the shelf occur in areas where relic sediments are found, and/or where authigenic minerals and large accumulations of shell fragments form part of the deposit.

There is a tendency for the shelf sediments to show better sorting near the edge of the shelf, perhaps as a result of stronger currents or turbulence which tend to produce better sorting in the sediments.

With the exclusion of the area where the head of Redondo Canyon comes close to shore, the sediment pattern is essentially the same from shore to an offshore distance of four miles. This pattern consists of an offshore gradation from sand to sandy silt. The areas where relic sand is still exposed are probably areas where sediment by-passing takes place. Also, the shelf sediments are probably reworked occasionally and the finer fragments are removed during intermittent erosion and deposition.

At the head of Santa Monica Canyon, and inshore from the central shelf projection 4 to 6 miles from shore, there are sediments which are generally coarser than those nearer the coast. The existence of relic sediments near the surface indicates that sedimentation must be slow at present. This may be due to either a smaller supply on this section of the shelf, or to greater turbulence which prevents permanent

accumulation of finer material. Fine sediment may be deposited in this area, but is removed or reworked more often than in the areas close to shore.

The central shelf projection contains an area of rock and gravel, and the sediment distribution is patchy over the entire area. Topographic evidence indicates mounds and depressions. Sediments here contain authigenic mineral grains and shell fragments which are often considered to indicate an environment of non-deposition, yet the sediment containing these components is often fine grained with appreciable amounts of silt and clay. It is, therefore, an inescapable conclusion that a large portion of this area is receiving sediment. In all probability, deposits are accumulating in depressions on this surface, and the small prominences which are the loci of formation of authigenic minerals and of shelled animals are being swept free of sediment. Most of the gravel area is probably covered by fine-grained material, and gravel at the surface is limited to the vicinity of the rock outcrops.

The percentage of calcium carbonate increases in an offshore direction. It is generally low over most of the shelf and slightly higher on the offshore slopes. The exceptions to this distribution are the high percentages found in patches on the central shelf between Santa Monica and Redondo Canyons. Almost all the calcium carbonate is derived from shell debris. High percentages indicate that deposition in these regions is slow and that little sediment derived from land is deposited.

The highest values of organic carbon are found beyond the shelf break. The distribution follows closely the

topography and sediment size indicating that organic particles are selectively transported from nearshore and the topographic highs and deposited in deeper water in the same manner as detrital sediments. The high values near the Hyperion outfall indicate that here there is a faster rate of deposition of organic matter than can be oxidized, removed, or masked by detrital sediment.

Cores and borings, especially those close to shore, show extreme vertical variations in texture. These variations may be due to many factors, including (1) fluctuations in quantity of sediment reaching the bay from the watersheds and other sources, (2) redistribution during periods of especially strong turbulence in the bay or in periods of calms, (3) the deposits may be related to former positions of sea level, (4) formation of special topographic features or changes in bottom topography, such as offshore bars, which may allow the accumulation of unique deposits, and (5) slumping of sediments.

It is likely that many of the textural changes in the cores from the submarine canyons are the result of slumping.

The clays and vegetation found in cores nearshore and also in borings made on land close to shore are believed to be due to deposition behind offshore bars. Landward migration of sand from these bars may be the source of the sand in the El Segundo Sand Hills.

Relation of Transportation and Deposition of Sediment
to Discharge of Sludge into the Bay

Existing patterns of sediments in Santa Monica Bay indicate that oceanographic conditions which cause the deposition and transportation of the sediments may fluctuate enough in some areas to create a condition of intermittent deposition and removal of fine-grained material. This condition seems to be especially true near the head of Santa Monica Canyon and along the inshore side of the central shelf projection where sands and silty sands are composed of a relic coarse fraction plus a fine fraction deposited from suspension. The preservation of relic material in these surface sediments indicates that although the fine silt can deposit here, often the sediments are reworked and most of the fine material resuspended. This area is in the vicinity of the end of the sludge outfall.

Currents in this portion of the bay flow toward shore during most of the year. It is evident that particles of sludge emanating from the end of the outfall which go into suspension will move shoreward as they settle. However, it is also important as a result of information collected on sedimentation in the bay to recognize the possibility of resuspension and further movement toward shore of any sludge accumulating in these areas of the shelf. Thus, there is a distinct possibility that sludge accumulating near the end of the outfall and at a distance inshore might be carried progressively toward shore by repeated resuspension and current motion and form a sludge deposit at a point intermediate between the end of the outfall and shore.

Areas of Rock Bottom

Rocks occurring in Santa Monica Bay are classified into three groups; (1) bedrock, (2) gravel (transported rock), and (3) phosphorite (a chemically precipitated rock).

Bedrock

The major area of bedrock exposed on the sea floor occurs on the outer shelf projection between the two submarine canyons, and rocks that are believed to be in place occur off Malibu and the Palos Verdes Hills. The major rock types found on the outer shelf are shales, but mudstones, siltstones, and sandstones also occur. Some of the rocks have been dated as Miocene in age. Fragments of schist recovered from the outer shelf are either basement rock (Jurassic or older) or from a Miocene-age breccia. Other investigators have dredged rock from the Redondo or Santa Monica Canyons.

Gravel

There are extensive patches of gravel in the nearshore region, off Palos Verdes Hills, and near Malibu. Gravel in extensive quantities is known to underly finer sediment in other parts of the bay, but the full extent is unknown. Some material of gravel size also occurs in the fine sediment of the bay, but is widely dispersed. The gravel fragments are primarily composed of igneous rocks with lesser amounts of metamorphic and sedimentary material. The major gravel deposit far offshore is surrounded by finer sediment, indicating that it is relic and was not transported to this

location during the present cycle of sedimentation. It was probably transported and deposited in the littoral zone during a Pleistocene lowering of the sea. Its source was the bedrock outcrops nearby and/or fluvial transport to its present location by streams flowing from the east - presumably Ballona Creek. The gravel is flanked by coarse-to medium-grained sand containing a great proportion of rock fragments. These rock fragment sands are thought to have been deposited at the same time as the gravels.

Phosphorite

Phosphorite occurs in the sediment over the outer shelf and on the outer edge of the shelf south of Redondo Canyon. The presence of phosphorite is indicative of slow or non-deposition of sediment in these areas.

Geologic Structure

The increase of the thickness of overburden in a shoreward direction from the central shelf projection indicates that the bedrock area is high and that a trough exists nearshore where great thicknesses of sediments have accumulated.

Two theories are presented to explain the geologic structure of the outer shelf; (1) a continuation of the Palos Verdes fault zone into the bay in which the outer shelf has been uplifted in relation to the nearshore area, or (2) the underlying consolidated rock dips gently toward shore with bedrock exposed on the outer shelf.

The absence of schist among the rocks dredged from Santa Monica Canyon by other investigators may indicate that the

area north of the shelf projection has been down-faulted, or tilted to the south.

The geologic structure of the bay is not considered to be unique and faults are probably as numerous as on land. In addition, it is likely that faulting is as active in the bay as elsewhere in the southern California region. Although there is no topographic expression of faulting on the shelf, data strongly suggest one or more major faults. It is not known whether the outfalls cross active subsurface faults. However, since there is no surface expression of faulting along the proposed outfall route, it may be presumed that no vertical displacement will occur even if the faults are now active.

Earthquakes resulting from movements along active faults, either within the bay or elsewhere in the region, should be regarded as probable. A long rigid outfall on unconsolidated sediments may then be subjected to considerable stresses.

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