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BUDGET OF LITTORAL SANDS IN THE VICINITY OF POINT ARGUELLO, CALIFORNIA

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ABSTRACT

This report shows the results of a detailed analysis of the various littoral processes which affect the California Coast between Pismo Beach and Santa Barbara. The method involves the concept of a sand budget based on the transport rates of all significant littoral processes. Each process is examined to assess the sedimentary contributions (credits) and losses (debits). To balance the sediment transports, the region is subdivided into five cells, the boundaries of which are chosen at positions where the longshore transport of sand has been estimated. Using basic data from maps, surveys, aerial photographs, climatic records, and wave conditions, the authors have determined a quantitative transport rate for each process in each cell. The results are shown in graphic and tabular form. The budget concept provides a practical tool for coastal engineering problems. However, the difficulty of moving from qualitative trends to quantitative determinations reveals gaps in the present state of knowledge and requirements for further research.

FOREWORD

The Coastal Engineering Research Center (CERC) is publishing this report to provide coastal engineers with a further, more detailed, study of a possible method for estimating the amount and rate of transport of littoral materials in a problem area.

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NOTE: Comments on this publication are invited. Discussion will be published in the next issue of the CERC Bulletin.

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ABSTRACT

The processes associated with the transport of sand were studied along the California coast between Pismo Beach and Santa Barbara. Quantitative estimates were made of the supply and loss of beach sediments and of the rates of sediment transport so that a budget of beach sand could be made for the area.

Estimates of the rates of longshore transport of sand were obtained from calculations of the longshore components of wave power. North of Point Arguello, the littoral transport is generally southerly at an estimated rate of about 60,000 yds^3/yr. Just east of Point Conception, the transport is about 100,000 yds^3/yr; this rate increases towards Santa Barbara, which has a measured rate of sand entrapment of 280,000 yds^3/yr.

The Santa Maria and Santa Ynez Rivers are the main sources of beach sand. The building of major dams on these rivers has significantly reduced this supply. A considerable loss of sand from the northern beaches due to wind action is evidenced by extensive dunes built inland between Pismo Beach and Purisima Point. This represents the only major sand loss from the beaches apart from the general longshore movement.

Estimates were made of the importance of diffusion processes. The spread of beach sand due to the multiplicity of the directions of wave attack was found to be given by a one-dimensional, Fickian diffusive process with a diffusion coefficient of 0.5 ft^2/sec. Rough estimates of the diffusion of water in the nearshore region were made using the scant literature available.

INTRODUCTION

This report deals with the sedimentary environment and the movement of sediment in the vicinity of Point Arguello, California. Both of these features are, to some extent, a function of the wave and current conditions in the nearshore region; therefore, some estimate of the water movement has also been made.

In addition to its purely practical importance, this type of study raises some interesting questions about our present level of understanding of the natural, sedimentological processes in a complex region such as this. The results of this investigation suggest that a reasonable delineation of the principal processes operative in sediment transportation can be achieved using the basic data of maps, surveys, and climatic and wave conditions. However, the difficulty of transition from qualitative to quantitative understanding reveals the gaps in the present state of knowledge. Throughout this paper the concept of a sand budget, essentially a continuity condition, is used to estimate unknown or poorly defined sediment transport rates from those which have been more accurately determined

The basic data for this study have been assembled from the following sources:

(a) Beach Survey - Pismo to St. Augustin, California, prepared by Ocean Science and Engineering (1964).

(b) Longshore components of seasonal wave power calculated for four locations near Point ARguello, California, prepared by Marine Advisers (1964).

(c) Previous work in this area and also in the area to the south, i.e., Santa Barbara and Ventura, available in the published literature (e.g. Johnson, 1959; Wilson, 1959; and Worts, 1951).

(d) Such surveys and maps as exist for this region (e.g. University of California 1945; Santa Maria Sheet, Geologic Map of Califoenia, California Division of Mines, 1959).

I. CHARACTERISTICS OF THE REGION

The study area, containing some 65 miles of California coastline between Pismo Beach and St. Augustin, is shown in Figure 2. The region of interest extends from the watersheds in the mountains, westward to the edge of the Continental Shelf, delineated on the figure by the 600-foot (100-fathom) contour. The area includes Point Conception, which marks a major change in the alignment of continental border of the west coast of North America - an abrupt change which produces important changes in coastal climate and in the exposure of beaches to wave action.

Land topograpny consists of a series of east-west trending ridges and valleys formed by folded and faulted marine sediments of Tertiary and Cretaceous age. Near the shore, the ridges form the major headlands of Point Sal, Purisima Point, Point Arguello (Figure I), and Point Conception. The coastal portions of the ridges do not exceed elevations of 500 to 2,000 feet: however, their inland portions are higher than 6,000 feet. Near the coast the valleys are wide with floors near sea level. The two principal valleys, the Santa Ynez and the Santa Maria, were cut well below present sea level during past glacial stages; the present streams meander on a depositional flood plain of stream sands and gravels. The coastal portions of the two valleys are boxed by fields of sand dunes which, due to the prevailing onshore wind, are actively migrating inland. (Figure 3).

The Continental Shelf, bordering the northern portion of the area, has a width of approximately 10 to 15 miles between the 600-foot depth contour and the shoreline. No submarine canyons traverse the broader north-south trending portion of the Continental Shelf; however, a series of submarine canyons occur on the continental slope about 5 miles west of Point Arguello, where the shelf narrows and turns easterly into Santa Barbara Channel.

a. Climate

In general the climate is transitional between that of southern California and that of the San Francisco region. Rainfall occurs in winter and early spring, averaging as much as 40 inches per year in the eastern mountains (Wilson, 1959, p. 10) (30)* , and as little as 10 inches near the coast. The yearly precipitation records for the area show large variations with time. At Santa Barbara (44 miles east of Point Conception), where records have been maintained since 1868, precipitation has ranged from a low of 4.5 inches in 1877 to a high of 45.2 inches in 1941. The principal wet years during this century were 1903-11, 1914-18, and 1935-41. The region has been subjected to a period of extended drought since 1944.

Temperatures vary seasonally in the fifties and sixties along the coast and more sharply inland. Predominant sea breeze winds are from the northwest with velocities averaging between 10 and 20 knots. The foam lines and slicks produced by this type of wind are clearly visible in Figure 1. The landward migration of sand dunes (Figures 3 and 4) resulting from these winds indicates their importance during the past few centuries.

b. Waves and Currents

A combination of wave hindcasting and wave recording was used to estimate the frequency of occurrence of various significant wave heights and wave periods in deep water off Point Arguello (Marine Advisers, 1964) (17). Waves originating in the North Pacific Ocean were hindcast from weather maps of the northern hemisphere for the six years 1936-38 and 1956-58. These hindcasts were supplemented by visual observations from research ships. The hindcast period includes three wet years (1936-38) and their associated storms, as well as three dry years. However, the storms for the period 1936-38 were not as severe as for many periods during the past century or the earlier parts of this century. Waves originating in the South Pacific Ocean were estimated by a combination of hindcasting from southern hemisphere weather maps for the period July 1948 through December 1950 and shore recording for the period July 1948 through January 1952.

To distinguish seasonal trends the year was subdivided into three parts, "winter" including December, January, February, and March; "transition" including April, May, October, and November; and "summer" containing June, July, August, and September. The principal wave direction in all seasons was from 320°, as was the predominant wind direction.

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* Numbers shown in this manner refer to LITERATURE CITED on page 19.

Wave refraction theory was used in computing the longshore components of wave power from the deepwater characteristics (Table I). The net values of wave power indicate the direction of longshore movement of both water and sediment. Field observations of currents between April and September, 1964 (Ocean Science and Engineering, 1964) (19) always showed longshore currents flowing to the south with intermittent rip currents breaking seaward in a southwesterly direction (Figure 5). This seems in good agreement with the calculations. Plumes of discolored water extending seaward to the south of Point Arguello observed on aerial photographs further confirm the southward tendency.

The application of the longshore component of wave power to the longshore transport of sand is discussed in the section, Longshore Transport, on page 6.

c. Beaches

The most noticeable features of the coastline are the three long, nearly straight beaches, facing west-northwest between Pismo and Point Arguello. The three headlands of resistant rock, Point Sal, Purisima Point, and Point Arguello have acted as natural groins, causing the beaches to align nearly perpendicular to the principal direction of wave approach. This alignment is reflected by the 30-foot and 60-foot contours but not at all by the 120-foot and deeper contours which run approximately parallel to the 600-foot contour shown in Figure 2. The effect of this beach alignment is to reduce the ratio between the net longshore wave power and the total longshore wave power, and hence to reduce the longshore transport of sediment.

These beaches all narrow and steepen as one moves from north to south, and the sand becomes correspondingly coarser. For example, profiles I N to 4 N (Table 6) show a steady increase in grain size for the nearshore samples; a similar increase can be seen between stations 7 N and 8 N; and 9 N and 10 N. The sand is predominantly quartz with some feldspar and small quantities of heavy minerals and rock fragments. Virtually no calcareous material is present. Trask (1952)(23) used heavy minerals as natural tracers in examining the sand movement between Monterey and Santa Barbara; some of this data will be relevant to the discussion of the sand budget.

Between Pismo Beach and Mussel Point the beach is backed by extensive dune fields which are actively moving inland due to the influence of the prevailing northwest winds (Figures 3, 4). The sand supplied to these dunes represents a very substantial loss of sediment from the beach.

Mussel Point and Point Sal are two rocky promontories separated by a 1.5 mile long beach backed by high cliffs (Figure 4). The cliffs consist of some 20 feet of grey, highly folded shales of the Monterey formation overlain by poorly consolidated, yellowish-brown sand of the Orcutt formation which holds the steep vegetation-covered slope up to elevations of 400 feet. These cliffs are subject to both wind and wave erosion and supply considerable quantities of sand to the beach.

Between Point Sal and Purisima Point the beach is backed by low, well-vegetated dunes (Figure 5). Purisima Point itself is a feature of very low relief. It consists of shale beds exposed along an arcuate outcrop extending out to sea for about 1,000 feet (Figure 6).

In the neighborhood of Surf, there is a small, poorly developed field of dunes, consisting of a series of closely spaced ridges which have a pronounced elongation to the southeast. South of Surf the backshore ends against a steep uniform slope, which consists of the semi-consolidated sands of the Orcutt formation with an occasional outcrop of shale at the base. This slope is covered with vegetation and rises to some 200-250 feet (Figure 8).

South of Point Arguello the character of the coast changes; the beaches are less well developed, being either pocket beaches bordered by headlands or narrow beaches backed by high cliffs. Between Point Arguello and St. Augustin the coastline is generally backed by a flat, vegetation-covered, marine terrace 60-80 feet above the beach. The beach is narrow and lies at the base of nearly vertical cliffs, cut into the loosely consolidated terrace material which is being actively eroded (Figure 9).

Long-term trends in coastal erosion and accretion were studied by comparing present beach profiles with earlier surveys (Ocean Science and Engineering, 1964 (19). Two beach profiles were surveyed at each of the fifteen locations shown in Figure 2. Each pair of profiles was run along parallel lines spaced about 1,500 feet apart. The northern profile for each pair is shown in Figures 10, 11 and 12, and the median diameter of the sediment sampled along each profile is listed in Table 6.

d. Drainage

The watershed for streams entering the ocean in the study area has a total area of about 3,600 square miles. The main watercourses of the area are shown in Figure 2. Although most of the streams are intermittent in nature, since their usual flows are small or nonexistent, their periodic floods bring large quantities of sediment to the coast. The southward flowing watercourses (southeast of Point Conception) consist of a number of short creeks flowing in arroyos with steep gradients; these are dry almost all the year. The westward flowing watercourses consistsof a few small streams and creeks and two large rivers, the Santa Maria and the Santa Ynez. Both these rivers have a small but continuous flow, although it is not always sufficient to prevent the beach from building completely across the river mouth (Figure 7). These two rivers, especially in time of flood, are also the most important contributors of river sediment to the coast.

Before regulation by the construction of dams, the Santa Maria and the Santa Ynez had a combined drainage area equal to nearly 80 percent of the watershed for the entire study area. Following the construction of Vaquero Dam on a tributary of the Santa Maria River in 1957 and the Cochuma Dam on the Santa Ynez River in 1953, the effective drainage basins were reduced respectively from 1,843 to 630 square miles and 924 to 480 square miles.

The effect of this reduction on sediment yield is discussed in the section, Stream Transport, on page 10.

2. SOURCES AND BUDGET OF LITTORAL SEDIMENTS

Application of the principle of conservation of mass to the sediments in the littoral zone has proved to be a very useful tool in evaluating the relative importance of the various possible sources of sediment and agents of transport. The procedure, sometimes referred to as the budget of sediments, consists of assessing the sedimentary contributions (credits) and losses (debits) and equating these to the net gain or loss (balance of sediments) in a given sedimentary compartment. The surprisingly large amounts of littoral sediment trapped by coastal engineering structures, such as harbors, groins, breakwaters and jetties, have led to our present insight into the high rates of littoral transport by waves and currents.

A schematic representation of the sediment budget is given in Figure 14. A table listing possible sources and sinks for a littoral sedimentary budget is given below:

CREDIT	DEBIT	BALANCE
Longshore transport into area	Longshore transport out of area	Deposition or Erosion
Onshore transport	Offshore transport	
Wind transport in	Wind transport out	
River transport	Deposition in submarine canyons	
Biogenous deposition	Solution	
Hydrogenous deposition	Mining	

Not all these possible factors are of importance in the Point Arguello region. For example, biogenous materials, such as shell fragments, which may be the major constituents of tropical beach sands, are less important in temperate climates. This is true of the study region, where quartz sand, rock fragments and heavy minerals constitute at least 90 percent of the sand. Also, hydrogenous material (i.e. that precipitated inorganically from seawater) was found to be unimportant to the budget of sediments in the vicinity of Point Arguello. However, it is of interest to consider each of the other mechanisms in turn, to discuss the method of estimation of the magnitude and distribution of the supply or removal of sediment and to attempt to evaluate the range of error of this estimation.

a. Longshore Transport

In the absence of direct measurements of the longshore transportation of sand in the area, two indirect methods were applied. The first is based on the dilution of the heavy mineral augite in the beach sand samples, and the other upon the longshore component of wave power.

b. Dilution

To look at the longshore movement of sand it is convenient to stretch the area of study to include Point Buchon to the north and the city of Santa Barbara to the south. There appears to be little net southerly sand movement at San Luis Obispo Bay, just north of Pismo Beach. Thus, it appears that the sand transport around Point Buchon must be fairly small. The known rate of entrapment of sand at the breakwater at Santa Barbara, 280,000 yds^3 per year (Johnson, 1953)(12), combined with the data of Trask (1952, 1955) (23,24), gives a method of checking the calculated longshore transport rates at Surf and Gato. Trask, looking at the heavy minerals (1952) and the beach profiles and sediment properties (1955), showed that sand was transported around Point Arguello and Point Conception, and that at least some of the sand reaching Santa Barbara came from north of Point Arguello. The mineral augite is certainly not supplied to the beaches south of Purisima Point (Trask, 1952); from the present study it appears that little sand is lost from the beaches south of the dunes at Surf, there being no obvious dune building and no submarine canyons nearshore. It is, therefore, reasonable to suggest that most of the sand passing Surf, including the augite it contains, eventually reaches Santa Barbara. If this is the case, the sand transport at any station south of Surf, multiplied by the percentage of augite in the sand, should give a constant product, which is the transport rate of the augite.

Unfortunately, Trask gave augite content as a percentage of the heavy mineral fraction, rather than the total sand sample. A further assumption then has to be made that the new sediment supplied to the beach contains approximately the same percentage of heavy minerals as the beach sand in transport, but no augite. The whole method may be justified by the fact that having made these assumptions the results obtained are rather good. The sand at the mouth of the Santa Ynez River (Surf) has an augite concentration of 15 percent of the heavy mineral fraction, Point Conception and Gato around 10 percent, and Santa Barbara 3-4 percent. Using the figure of 280,000 cubic yards per year for the longshore transport at Santa Barbara, this method gives transports of about 65,000 cubic yards per year for Surf and 100,000 cubic yards per year for Gato, in good agreement with the values calculated from the longshore wave power discussed below.

c. Longshore Component of Wave Power

Waves traveling over a sand bed exert a stress on the bed, which if sufficiently intense, will produce a to-and-fro motion of sand. Since the waves supply the energy to set the sand in motion, any net current will produce a transport of sand in the direction of the current. Thus, the transport of sand should be proportional to the product of the amount of wave energy dissipated and the velocity of the current. For the special case of the longshore transport of sand in the surf zone, the breaking wave supplies the power for placing sand in motion, as well as the longshore current that carries the sand load.

Observations show that the mean value of the longshore current is proportional to the breaker angle (angle between the breaking wave and the shoreline). Therefore, it appears reasonable that the longshore transport of sand should be proportional to the longshore component of wave power. The validity of the general concept that sand transport is proportional to the dissipation of wave energy has been partially verified by experiments in a wave channel (Inman and Bowen, 1963 (8)). Verification of the more complex application of this principle to the longshore transport of sand in the surf zone is less certain. However, the few field calculations presently available (Caldwell, 1956 (1); Saville, 1962 (22); and Manohar, 1962 (16)), together with the laboratory data (Savage, 1962 (21)), indicate that the longshore transport of sand is directly proportional to the longshore component of wave power.

Therefore, the budget of wave energy was computed as described under the section, Waves and Currents, on page . The longshore components of wave energy for four sections of coastline are listed by season in Table I.

The calculations were obtained by the following relation. The instantaneous longshore component of wave power per unit length of beach is given by

$$P_e = E_o C_o n_o \frac{b_o}{b_b} \sin\alpha_b \cos\alpha_b$$

where the subscripts "o" and "b" refer to waves in deep water and at the breaking point respectively, $E_o = \frac{1}{8} \rho g H_o^2$ is the energy per unit surface area in a progressive wave traveling in deep water with phase velocity $C_o = gT/2\pi$ and group velocity $C_o n_o$, and ρ, g, H_o, t are respectively the density of the fluid, the acceleration of gravity, the root-mean-square deep water wave height, and the wave period. b_o is the separation between wave rays in deep water, and b_b is the separation at the breaker point, and α_b is the angle the breaking wave makes with the shoreline. The ratio b_o/b_b is the reduction in energy per unit length of wave crest due to wave refraction, and $\sin\alpha_b \cos\alpha_b$ converts to longshore component of wave power per unit of beach length. In our calculation the breaker angle α_b is positive when the longshore component is towards the south or southeast (downcoast).

The data listed in Table I are the sums of the various instantaneous longshore powers, P_e, multiplied by the times during which they occurred, which gives energy per unit distance along the shore.

The semi-empirical relation between the longshore transport of sand, S in ft^3/sec, and the instantaneous longshore component of wave power per foot of beach, P_e in ft-lbm/sec^3, is taken as

$$S = 1.13 \times 10^{-4} P_e$$

where lbm is pounds mass. *

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* Note that 1 ft-lbm/sec^3 = 1 ft-poundal/ft-sec = 1/32.2 ft-lbf/ft-sec, where lbf is pounds force.

This relation is obtained from the field and laboratory data by requiring that the best-fit curve retain the direct proportionality between S and P_e as indicated by theory. The estimates of the seasonal and annual longshore transports of sediment resulting from the application of this relation are given in Table 2.

The stations north of Point Arguello (Santa Maria River, St4; San Antonio Creek, St8; and Surf, St9) all show large estimates for both upcoast (north) and downcoast (south) transports, with a small net transport of about 60,000 cubic yards/yr to the south. This is in keeping with the concept that the present beach alignment is maintained in a near equilibrium position by the natural headlands which act as large groins and cause the beach fillets in between to be nearly perpendicular to the prevailing waves. This is in contrast to the seasonal estimate for Gato (St15) east of Point Conception where the downcoast (east) transport is dominant for all seasons.

The computations of net longshore drift from wave power for the northern beaches are likely to be less reliable than for Gato because they are the differences between two large and nearly equal amounts. A one-degree change in beach alignment or in wave direction could result in large changes in the estimate for the net transport.

It seems likely that these beaches would adjust rapidly to compensate for changes in sediment supply. For example, floods on the Santa Ynez River should result in slight counter-clockwise orientation of the beach which in turn would result in an increased longshore transport until the beach readjusts to its former alignment.

d. Onshore-offshore Transport

One of the more difficult parameters to determine accurately is the rate of accretion or erosion of sediment on the beach or shelf. The seasonal changes in the sediment distribution due to the variations in the wave conditions are often much larger than the net annual change. A further difficulty in evaluating the changes on the shelf is that a relatively small change in the sediment level over a wide area requires a large quantity of sediment.

Profiles based on the hydrographic survey of 1933-34, made by the U. S. Coast and Geodetic Survey, are shown in Figures 10, 11, and 12 on page 31, together with the data taken during the beach survey in 1964 (Ocean Science and Engineering, 1964 (19)). The discrepancies in the rocky area of profile 5 N and in the rock and kelp beds of profiles 11 N to 15 N are probably the result of slightly different survey lines; however, the observed differences are rarely much larger than the accuracy of measurement and can only be used to indicate qualitative trends. The profiles of 1 N, 6 N, and 8 N suggest nearshore accretion; the profiles of 2 N, 3 N, and 4 N all suggest loss from the shelf, particularly 2 N; and this shelf area is, therefore, a possible source of sediment.

In June and July of 1945, a beach survey out to 30 feet below MLLW was made in the area between Pismo and Surf by a group from the University of California at Berkeley. Survey stations N1 and N9 were selected to correspond to stations of this survey. Beach comparisons showed that, in all cases, the changes in the nearshore region between 1948 and spring 1964 were of the same order as the changes between April 1964 and September 1964. The long-term change tended to be a slight net loss of sand from this area. Examination of the 1933-1964 surveys shows slight accretion in this region, so that the overall long-term changes in depths of 30 feet and less seem negligible; the small changes observed being a function of the time of observation.

e. Wind Transport

The extensive dune fields between Pismo Beach and Point Sal and the lesser fields to the south represent a large loss of sand from the beach by wind transport. Estimates of the sand loss from the beach due to the prevailing northwest winds are shown in Table 5. The rate of dune advance has been estimated on the basis of field measurements in the northern dune fields, with some additional evidence obtained from aerial photographs. This rate for the northern dune fields (Figure 3) is of the order of 2 feet per year or 0.005 feet per day (0.15 cm/day). Assuming a slip face slope of 30° and a mean dune height of 30 feet, the volume transport of sand becomes 0.15 ft^3 per foot of coast per day. The estimate is slightly higher than that provided by a local resident concerned with dune stabilization, who estimated a rate of advance of 1.0 feet or less per year in the vicinity of the mouth of the Arroyo Grande. On the other hand, the rate of 0.15 cm/day is rather lower than rates measured by Cooper 1958 (3) for relatively similar dunes of the Washington-Oregon coast. His rates were 0.17 cm/day for winter, 0.71 cm/day for summer, and0.44 cm/day yearly.

Because the dune fields south of Point Sal are less well developed and are partly vegetated, measurements of transport rates are more difficult. However, the decrease in size of the inland basins south of Santa Maria Valley, a factor bearing on the development of a strong sea breeze regime, also suggests that wind transport is somewhat less south of Point Sal. Therefore, the loss due to wind deflation along the beaches south of Point Sal was arbitrarily assumed to be two-thirds of that to the north, i.e., 0.10 ft^3/ft per day (see Table 3). It seems that the rate of advance estimated for the dunes in the study area is about the right order of magnitude but perhaps a little conservative. It was estimated from the wind regime that sand was returned to the beach by offshore winds at a rate of about 5 percent of the inshore transport rate.

f. River Transport

Johnson (1959) (13) has estimated the average rate of sediment transport of the Santa Ynez and Santa Maria Rivers for the years 1941 through 1954. These transport rates were calculated from the Einstein Bed Load Formula using river flow data from gauging stations some distance inland, 12 miles from the mouth of the Santa Ynez and 6 miles from the mouth of the Santa Maria River.

The average yearly transport of sediment past the gauging station on the Santa Ynez was estimated to be about 570,000 yds^3. This figure divided by the area of the river basin above the gauging station, about 820 mi^2, gives a sediment yield for the area of 700 yd^3/mi^2 yr. This figure agrees well with the expected yield of a river basin of this size that has an effective rainfall of 15-20 ins/yr (Langbein and Schumm, 1958, Figure 2) (15).)

However, if the same calculation is made for the Santa Maria River, using Johnson's estimate of 178,000 yds^3/yr for the sediment transport rate and an area of 1,800 mi^2, the resulting yield is only of the order of 100 yd^3/mi^2 yr. Much of the difference in yield between the two rivers must be related to characteristics of the drainage basins and to the extent of their flood plains, depositional areas which have been filling with stream sands since the last lower stand of sea level. The gauging station on the Santa Maria River is seaward of a large portion of the flood plain. This area removes rather than adds sediment to the stream load.

The gauging station on the Santa Ynez River is above the major flood plain around Lompoc. Hence, it is to be expected that some of the load passing this station will be deposited on the plain between the gauging station and the coast. These flood plain deposits are being mined at a rate which is not small compared with the present stream supply. This loss of material may have a considerable effect on the long-term changes of the rivers (see the section on Mining, page 13, and Johnson, 1959 (13).

The building of major dams on the Santa Maria and Santa Ynez has greatly reduced the effective areas of the drainage basins of these rivers. Also, the dams have removed much of the area of steep streams and active erosion from the effective area of the basin. No material eroded in the region of the headwaters can pass through the catchment lakes of these dams and reach the coast. The dams also reduce the intensity of the floods on these rivers as the reservoirs are filled at this time. Part of the dam design is specifically for flood control, either to absorb the excess water or spread the flood period and, hence, reduce the intensity of stream flow. This control greatly reduces the volume of sediment that the rivers can supply to the coast during these floods.

The Cachuma Dam on the Santa Ynez River reduces the effective drainage area by almost one-half. Much of the remaining area consists of flood plain and a rather small area of active erosion. The new morphology of the river is similar to that of the Santa Maria River. Therefore, it is estimated that the present yield should be of the order of 100 yds^3/mi^2 yr or 48,000 yds^3/yr.

The Vaquero Dam on the Cuyama River, the major tributary of the Santa Maria, has reduced that basin by about two-thirds, most of the remaining area being flood plain. Taking 100 yds^3/mi^2 yr as the present expected yield, gives a supply of some 60,000 yds^3/yr.

The San Antonio River, Arroyo Grande, and San Luis Obispo Creek, all of which have morphologies similar to that of the Santa Maria, also have an estimated sediment yield of about 100 yds^3/mi^2 yr.

The series of small creeks between Point Arguello and Santa Barbara should have about the same yield as the Santa Ynez before flood control, some 700 yds^3/mi^2 yr.

Table 4 shows the estimated annual sediment contribution of the various streams.

Ocean Science and Engineering (1964) (19), using flow data from the Santa Ynez for a large flood in 1958, estimated that 160,000 yds^3 of sand passed the station during a three-week period (Table 3). Rainfall data for this area suggest that some three out of ten years have a fall significantly above the average (Wilson, 1959, (30)). Hence, this figure seems to roughly correspond to the previous estimate using the concept of sediment yield.

g. Cliff Erosion

The rate of cliff erosion in the study area has been estimated from aerial photographs as generally of the order of 1 foot per year or less. For the area, the mean height of the 30 miles of cliffs is about 40 feet. However, the contribution of sand-sized material due to cliff erosion depends on the composition of the rock and its resistance to erosion. The Orcutt sandstones at Point Sal and between Surf and Point Arguello contain over 80 percent quartz of sand-size, whereas the alluvial cliffs around Point Conception are mainly clay and silt with small quantities of sand and gravel.

It is estimated that cliff erosion of the Orcutt sandstones from north of Mussel Point to south of Point Sal yields about 40,000 yds^3/yr of sand to the beaches. The estimate is based on an erosion rate of 1/2 foot per year for 18,000 feet of cliff with mean height of 150 feet and composed of 80 percent sand.

Similar calculations for cliff erosion in the vicinity of Point Arguello (Bear Valley to Sudden Flats), assuming an erosion rate of 1/2 foot per year for 40,000 feet of cliff with a mean height of 40 feet and containing 60 percent sand, indicate a sand yield of 25,000 yds^3/yr.

While there is cliff erosion east of this area, the percentage of sand in the alluvial cliff material is small and, consequently, the yield of beach sand is less important.

h. Deposition in Submarine Canyons

For much of the California coast the most important loss of sand is by deposition in submarine canyons. About 250,000 yds^3/yr moves down Scripps Canyon at La Jolla and is lost to deep water. The study area does not contain a significant canyon, and it appears that the offshore loss of sediment is small.

i. Mining

Johnson (1959, p. 245) (13) lists mining of river sands during the ten-year period 1945-55 as approximately equal to 433,000 cubic yards from the Santa Maria River and 111,000 cubic yards from the Santa Ynez River. During the same period 27,000 cubic yards were mined from the beach near Pismo. On an annual basis, these quantities are equivalent to two-thirds and one-quarter, respectively, of the estimated sediment yield of the Santa Maria and Santa Ynez Rivers. The present effect of mining on the yield of river sediment to the ocean is difficult to evaluate, as the location and configuration of the mining pits are not known. Consequently, these losses are not shown in Figure 15 on page 36. However, continued mining at these rates will eventually affect the sediment budget of the area.

j. The Budget for the Study Area

The estimated budget of sediments for the area is shown schematically in Figure 15. For the purpose of balancing the sediment transports, the region has been subdivided into five cells, the boundaries of these cells being chosen at positions for which the longshore transport of sand has been estimated. The calculated values of supply and loss of sand are also shown in Table 7, together with the values for the net change of sediment in the beach area. Although this table does not consider the onshore-offshore movement of sand, it can be seen that cells II, III, and IV have net changes that are negligible compared with the ranges of possible error in the estimates of transport rates. This helps to substantiate the hypothesis that most of the sand passing Surf eventually reaches Santa Barbara. This also indicates that, with the exception of longshore transport out of each cell, the only significant loss of beach sand in the whole region is the loss to the dunes.

The net deficit of approximately 100,000 yds^3/yr in cell I must be balanced by an onshore transport of sand from the shelf or by a longshore transport of sand around Point Buchon just north of the study area. Comparison of profiles run in 1964 with the U. S. Coast and Geodetic Survey of 1933 (Figure 10, N 2 and 3) suggests that the shelf has eroded. The flat slopes of 1 on 250 that are found between depths of 60 and 100 feet should permit the onshore migration of sand to be induced by the action of waves traveling across the shelf. Model studies show that waves traveling over a horizontal bed of sand produce a net transport of sand in a down-wave direction (Inman and Bowen, 1963) (8); it also seems likely that beach sediments on the coasts of Holland are derived in part from the floor of the North Sea.

While the source of sediment for cell I may include sediment transported onshore from the shelf and longshore from Point Buchon, the comparison of the profiles of 2 N, 3 N, and 4 N suggests that the shelf is being eroded and, hence, that the first mechanism is the more important. The observed changes are more than sufficient to supply the quantity of sediment required.

No estimate of the sediment supplied by cliff erosion in cell V has been made, as much of this coast was outside the area studies in the beach survey. It is, however, reasonable to suppose that cliff erosion along this considerable length of coastline could greatly reduce the quoted deficit of 30,000 yds^3/yr in this cell. The longshore transport of sand past Gato combined with the supply by stream transport and cliff erosion then supplies sufficient sediment to satisfy the known rate of entrapment at Santa Barbara, some 280,000 yds^3/yr.

3. SAND TRANSPORT AND DIFFUSION

a. Long-term Movements

In order to arrive at quantitative estimates of the sediment movement, it has been necessary to take long-term averages of the processes operative in the region of study. The wave regime has been considered in terms of mean seasons, the river data has to be averaged over the years to take account of the irregularity of the major floods, the changes in cliffs and shelf have been observed by photographs and surveys made some tens of years apart. In this way, trends can be observed that give a general picture of the processes that are molding the area. The time constant involved in the sedimentary processes was estimated empirically by the U. S. Army Engineers for the Santa Barbara area as being 5½ years.* Considering our state of knowledge and the information available, the methods used in the current study seem to be the most suitable way of approaching the problems of sediment movement.

The general trend of the sand movements can now be described with some confidence (Figure 15). There is an onshore movement of sand north of the Santa Maria River; most of this sand is supplied to the dunes between Pismo and Mussel Point. The sand can be assumed to migrate initially only to the first dune inland from the beach. The sand moves up the windward face of the dune, avalanches down the lee (or slip) face, and is buried within the advancing dune. It will be released again when the dune advances its own length. With measured rates of advance of the order of 2 feet/year, this may be many years.

The general trend of longshore sediment movement is to the south throughout the whole study area at a rate of about 60,000 yds^3/yr. This movement occurs principally in depths less than 60 feet (Trask, 1955) (24), although changes in sand level occur in greater depths (Inman and Rusnak, 1956) (11). The vertical depth of sediment motion is hard to estimate. Seasonal changes of sediment cover observed (Ocean Science and Engineering, (1964) (19) were not greater than 10 feet, but no observations were made of the winter conditions when greater changes may be expected to occur.

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*The U. S. Engineers derived an empirical formula for the sand movement around Santa Barbara as $5{,}000\ R + 350{,}000 = A$, where R is the rainfall in inches for a two-year period and A is the volume of the sand transport in cubic yards during a two-year period that begins 3½ years after the end of the period in which R was obtained (Norris, 1964) (18).

The dunes south of Point Sal are not continuous dunes, but broken and vegetated ridges with channels between them through which the sand may blow inland for some distance. This is also true for the area around Surf, although the dune field is not as extensive.

South of Point Arguello the sand movement is confined to the beach with no losses to dunes, except for one small dune near Point Conception. There appear to be no losses offshore in the study area; however, the effect of tidal currents or possibly the California Current, in causing sand to be lost off the shelf into deeper water, should not be overlooked. There are frequent bottom notations of sand and rock near the heads of Arguello Submarine Canyon.

The estimates for the budget of sediment shown in Figure 15 and listed in Table 7 are for the period following the construction of the dams on the Santa Maria and Santa Ynez Rivers. Prior to that time, the rivers yielded several times more sand than at present. It seems likely that the longshore transport rates were somewhat greater as a result of (a) slight changes in beach alignment associated with the deposition of stream sands and (b) somewhat more severe storms during former years producing greater downcoast components of wave energy (refer to discussion of longshore transport).

b. Short-term Processes

Although the annual trend is a southward longshore transport of littoral sediment, the seasonal trends show considerable variation (Tables 1, 2 on page 37). In winter the transport tends to be to the north, in transition and spring to be strongly to the south. However, in each season the total longshore power is much greater than the net power; this may be considered to cause a considerable diffusion of sand in relation to the net transport; the sand is "well-mixed" in the longshore direction. If a foot of beach length contains 5,000 to 10,000 cubic feet of sediment which moves during the year, the average movement of a single grain will be of the order of $\frac{9 \times 60{,}000}{7{,}500}$, that is, 70 yards. The sand initially on this foot of beach will be found to have assumed a Gaussian (or normal) distribution along the beach, the center of this distribution about 70 yards south of the initial position. However, the standard deviation, σ, of the distribution is of the order of 1 mile; that is, to find 95 percent of the original sand, one would have to cover 4 miles of beach.

The diffusion coefficient, K, for this type of process is a constant given by $K = \sigma^2/2t$ where t is the elapsed time. This relation gives a value of $K = 0.5$ ft^2/sec. for the diffusion coefficient of sand in the above example. Experiments carried out at Newport Beach using marked sand have confirmed the fact that sediment initially at one place on the beach will be found to have assumed approximately a Gaussian distribution along the beach at a later time (for example, see tracer counts for 14 and 21 August 1964 in IEC-Oceanics, 1966). The diffusion coefficient estimated from the observations was again of the order of 0.5 ft^2/sec.

Inman and Chamberlain (1959) (9) made a single study of the movement of sediment on the sea bed outside the surf zone in a depth of about 10 feet below MLLW; the waves were low (1 - 2 feet high) and of long period (13 - 15 seconds). The results showed that the diffusion was large compared to the net transport, although the diffusion coefficient itself was only about 0.01 ft^2/sec. The relatively small value of K is expected for two reasons; first, the sea was fairly calm and this region was outside the surf zone, and second, the effective diffusion in the previous cases was a combination of the effect of the diffusive action associated with a single wave train and the effect of the multiplicity of wave trains approaching from different directions at different times.

The water movements in the nearshore region follow the same directional trends as the sediment transports, the assumption being that the wave action lifts the sediment into suspension and the suspended material is transported by the prevailing currents of water. In the surf zone the longshore currents usually flow to the south, although this trend may be reversed during the winter months. Flows of several feet per second are usual in both the longshore and rip currents (Inman and Quinn, 1952) (10). The diffusion coefficient for water, even when the sea is fairly calm, is not likely to be less than 2.5 ft^2/sec in the surf zone (Harris et al, 1964) (5). The water outside the surf zone has generally been found to have a diffusion rate which is proportional to the 4/3 power of the extent of the patch under consideration (Wiegel, 1964, pp 424-441) (29) or to a constant times the size of the patch (Joseph and Sendner, 1958) (14).

Crew and Worrall (1964) (4) in their report of the diffusion studies in the Point Arguello region have used the theory of Joseph and Sendner to obtain a diffusion coefficient of 1.5r cm^2/sec, where r is the radius of the dye patch in cms. This gives a diffusion coefficient which increases from 1.5 ft^2/sec to 15 ft^2/sec during their experiments.

In general, this sort of data only exists for the conditions which held when the few good experiments, that gave the few good results that exist, were made. For other conditions these results must be used to estimate the order of magnitude of the phenomena. There is certainly a need for more work on the transport and diffusion of water in the nearshore region so that the way in which these respond to the various combinations of waves, winds, and bottom topography may be better understood.

4. RECOMMENDATIONS

The limitations of the methods and material used in this study suggest many areas in which further work should be done if realistic values of the critical parameters are to be obtained.

The first three suggestions relate specifically to problems encountered in this study, although the data so obtained might be of more general interest. The last three deal with the type of information required for any problem concerning the movement of water and sediment in the nearshore region.

1. A need exists for further beach and shelf surveys to differentiate the seasonal and long-term changes with some certainty.

2. Further studies of the sediment, especially the heavy minerals, are necessary.

3. A close look should be made of the region between Point Buchon and Pismo Beach to estimate the sediment influx from the north.

4. Studies are needed of the nearshore movement and diffusion of water, especially in and near the surf zone, so as to be able to predict these processes knowing only the deepwater wave regime and the beach topography.

5. Studies of nearshore movement and diffusion of sand are also required, especially examination of sediment movement as a function of distance from the shoreline and as a function of depth below the sediment surface.

6. More reliable methods should be developed for the prediction of river sediment load, a very old problem with many solutions, nearly all of which are unsatisfactory.

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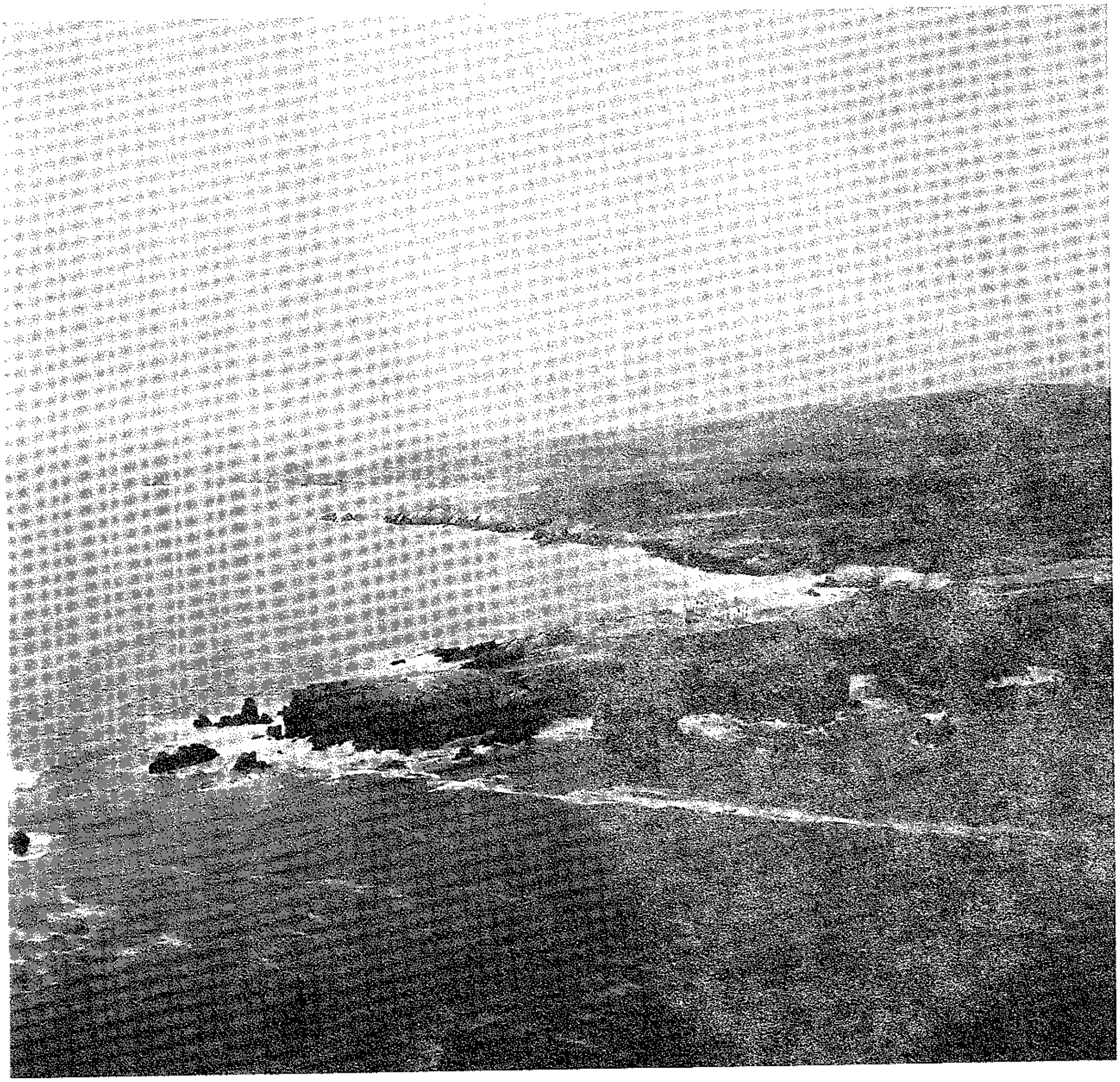

Figure 1. Point Arguello

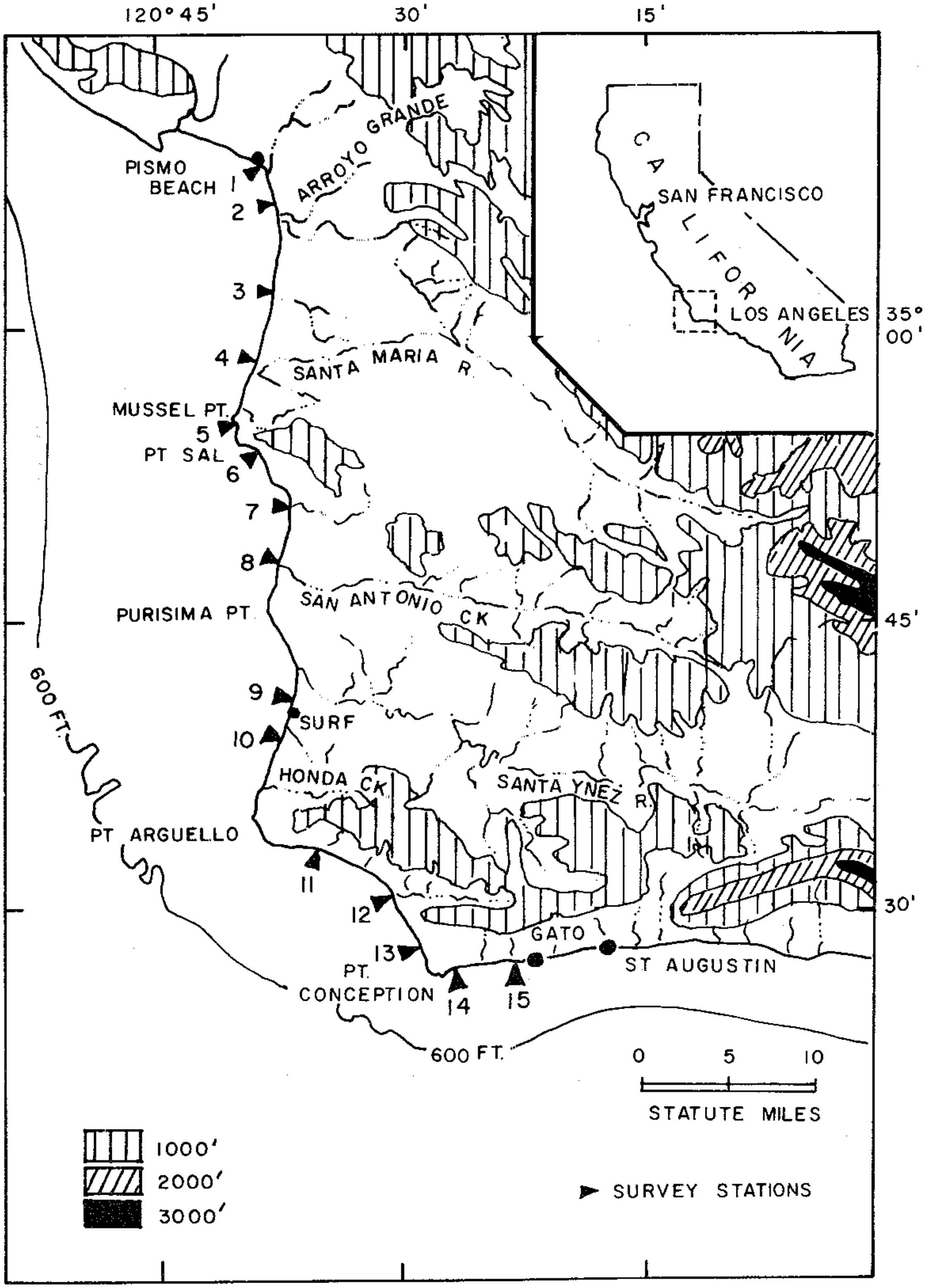

Figure 2. The Point Arguello Region

Figure 3. Sand Dunes South of Pismo Beach

Figure 4. Mussel Point

Figure 5. Dunes North of San Antonio Creek

Figure 6. Purisima Point

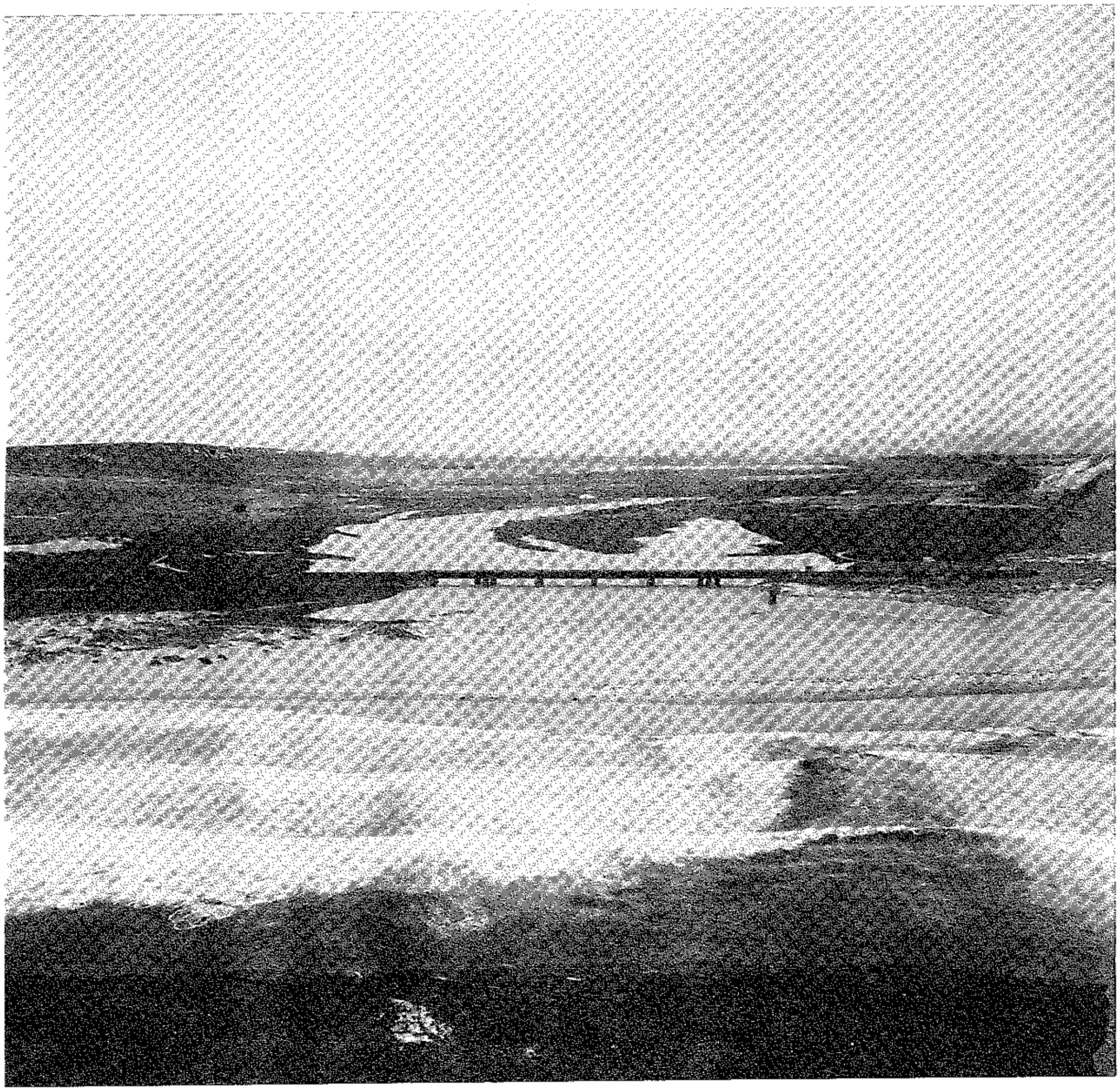

Figure 7. The Mouth of the Santa Ynez River Closed by Littoral Drift

Figure 8. Cliffs South of Surf

Figure 9. Cliffs Between Point Conception and Point Arquello

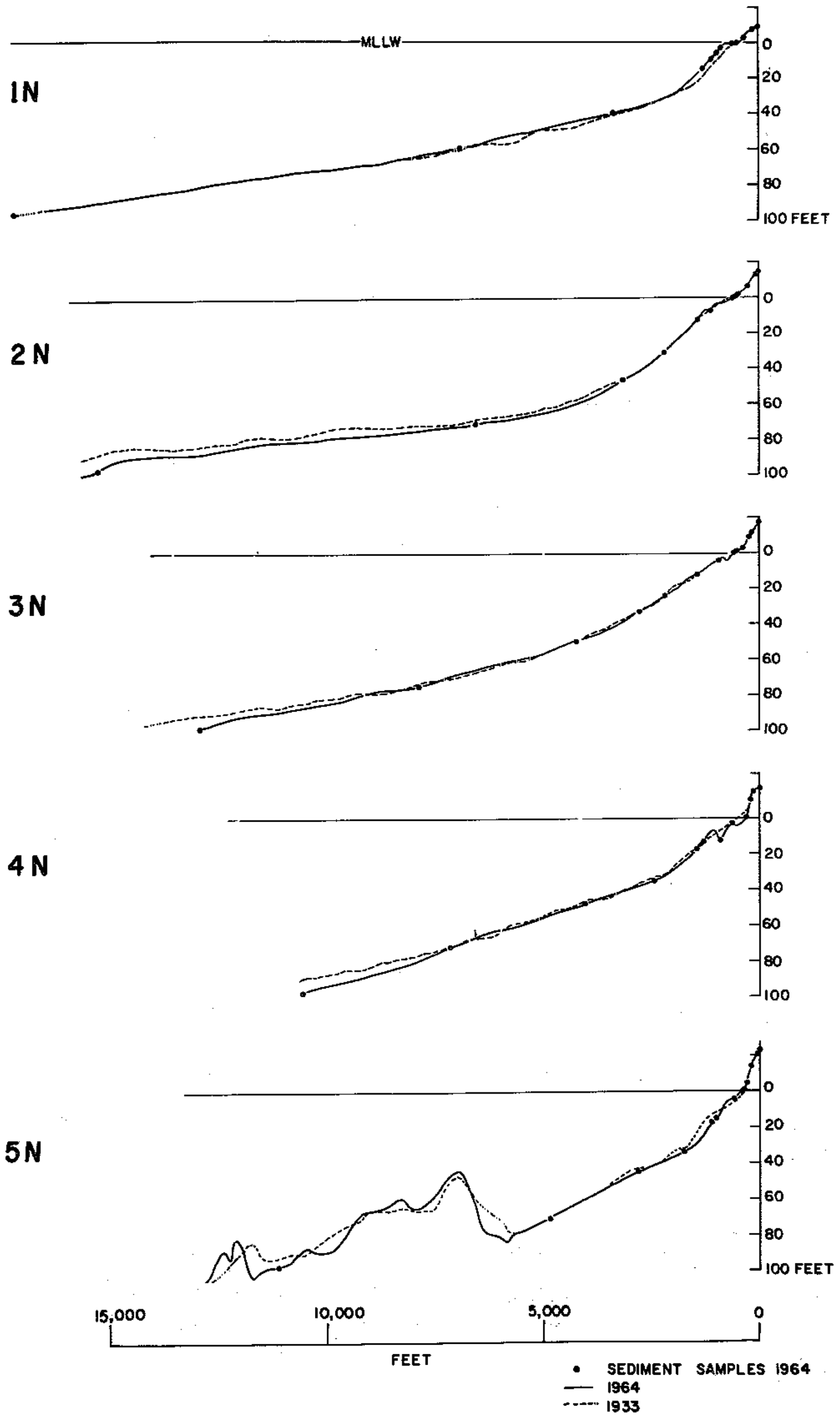

Figure 10. Beach Profiles, Pismo Beach to Point Sal

Survey stations for profiles are shown in Figure 2 (after Ocean Science and Engineering, 1964) (19)

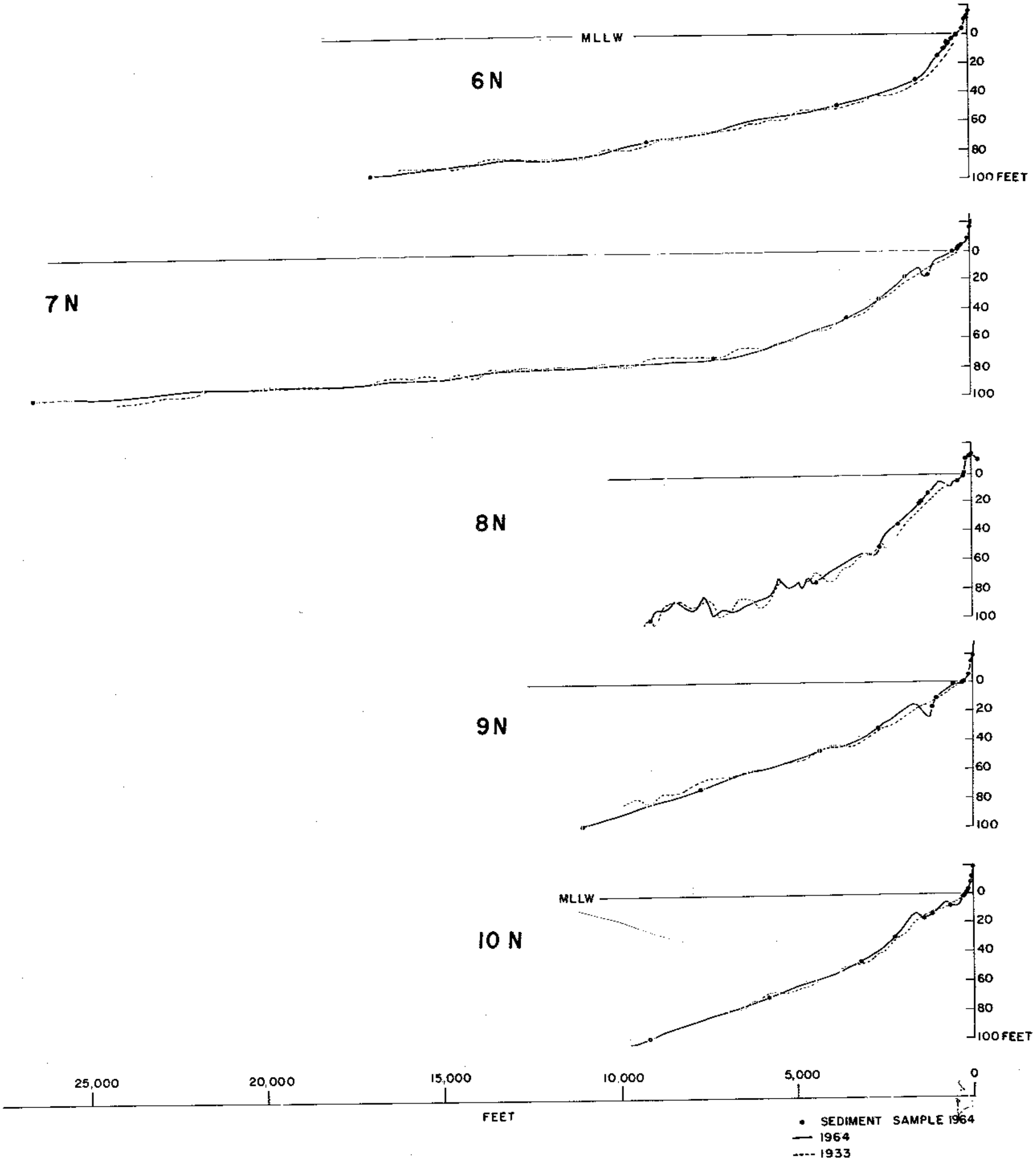

Figure 11. Beach Profiles, Point Sal to Point Arguello

Survey stations for profiles are shown in Figure 2
(after Ocean Science and Engineering, 1964) (19)

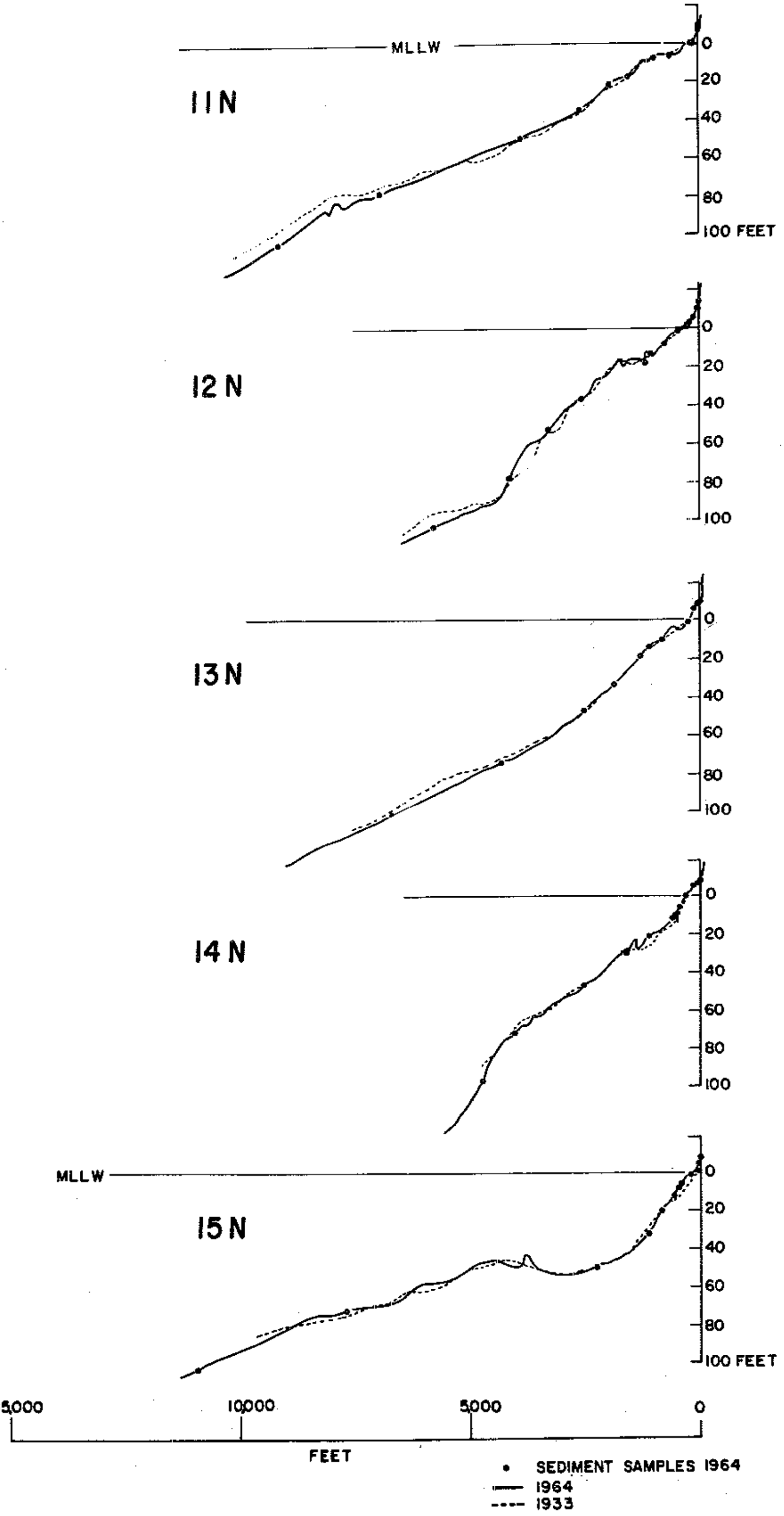

Figure 12 Beach Profiles, Point Arguello to Saint Augustin

Survey stations for profiles are shown in Figure 2
(after Ocean Science and Engineering, 1964) (19)

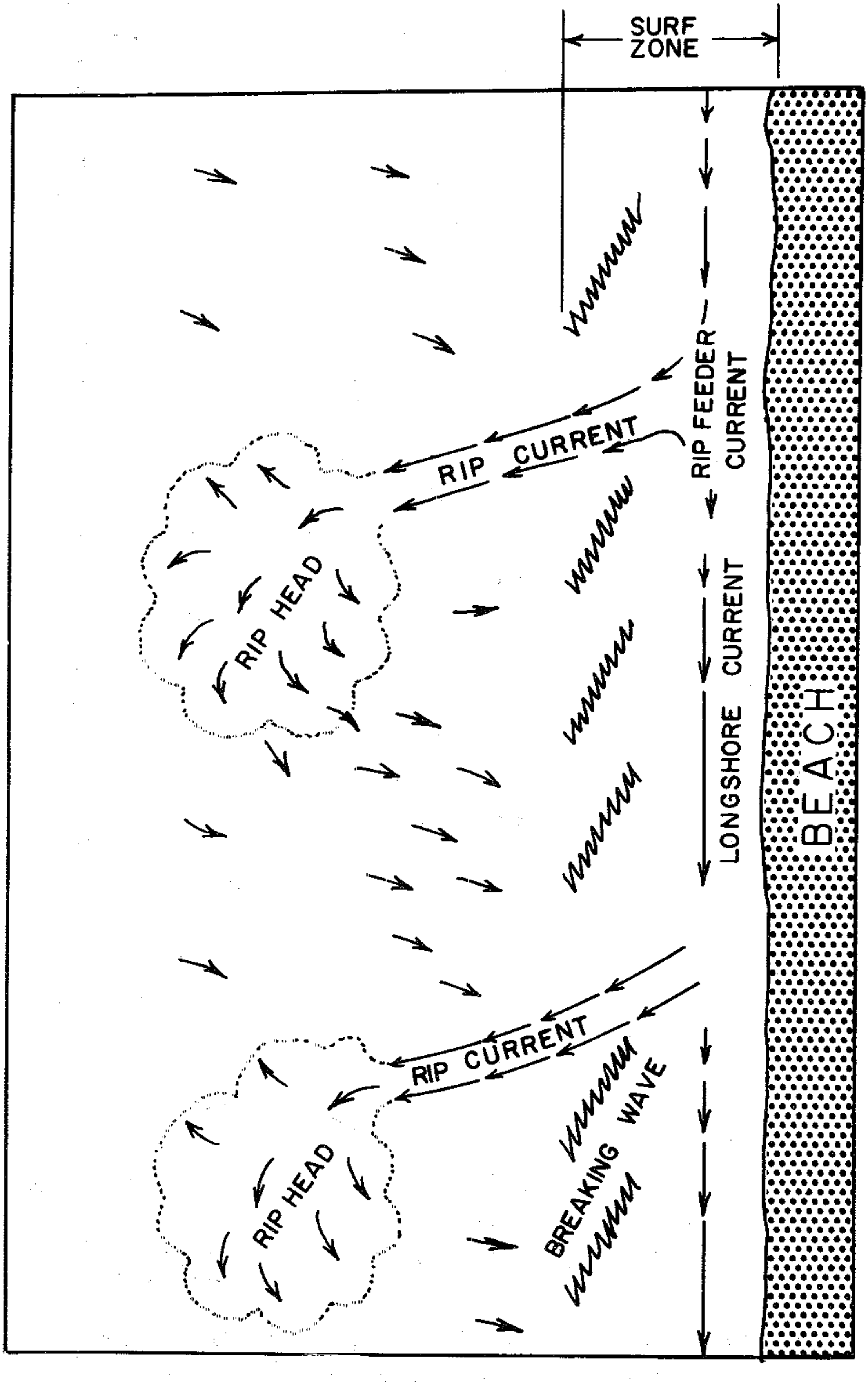

Figure 13. Schematic Representation of the Nearshore Circulation

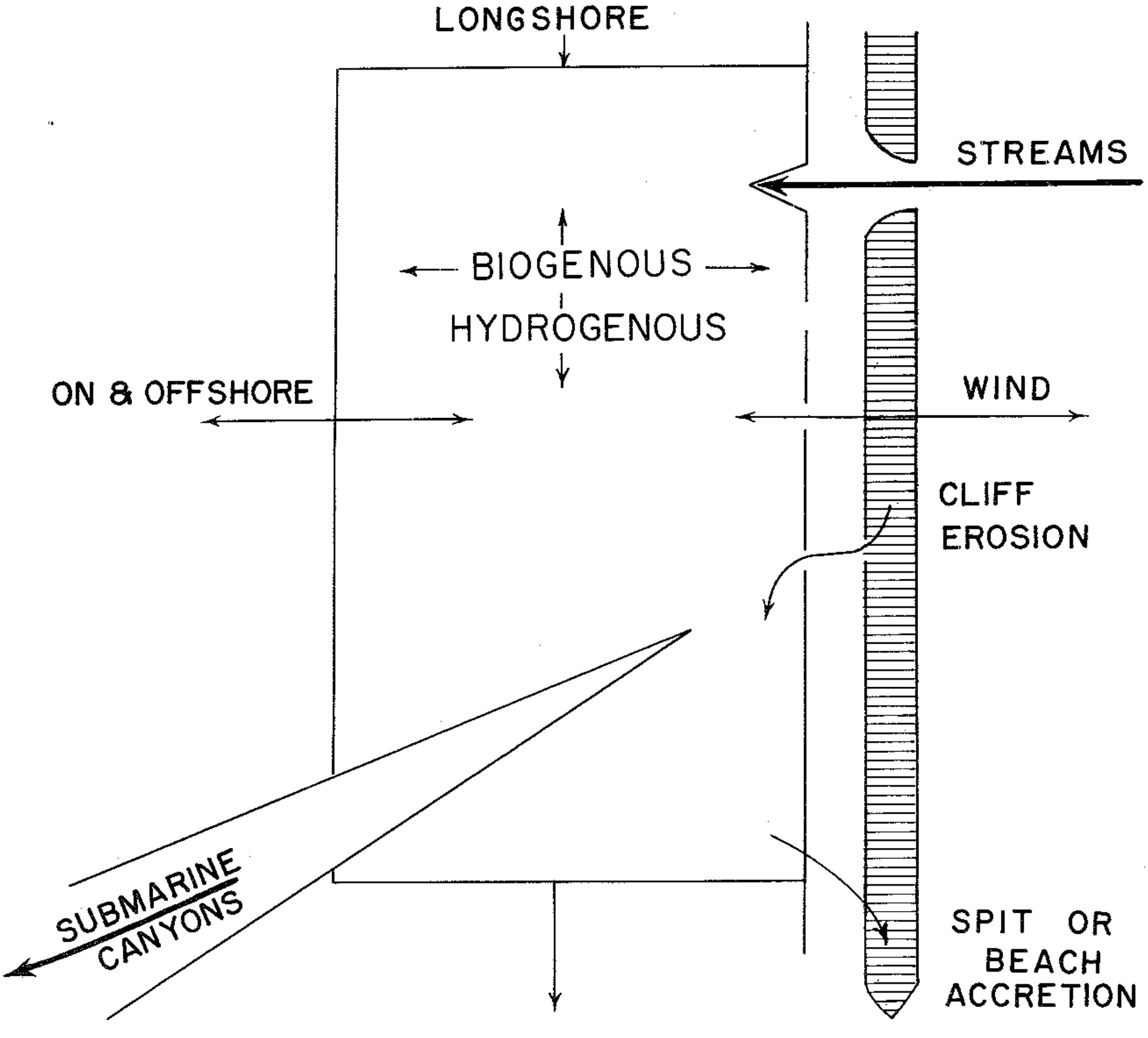

Figure 14. Schematic Representation of the Sediment Budget

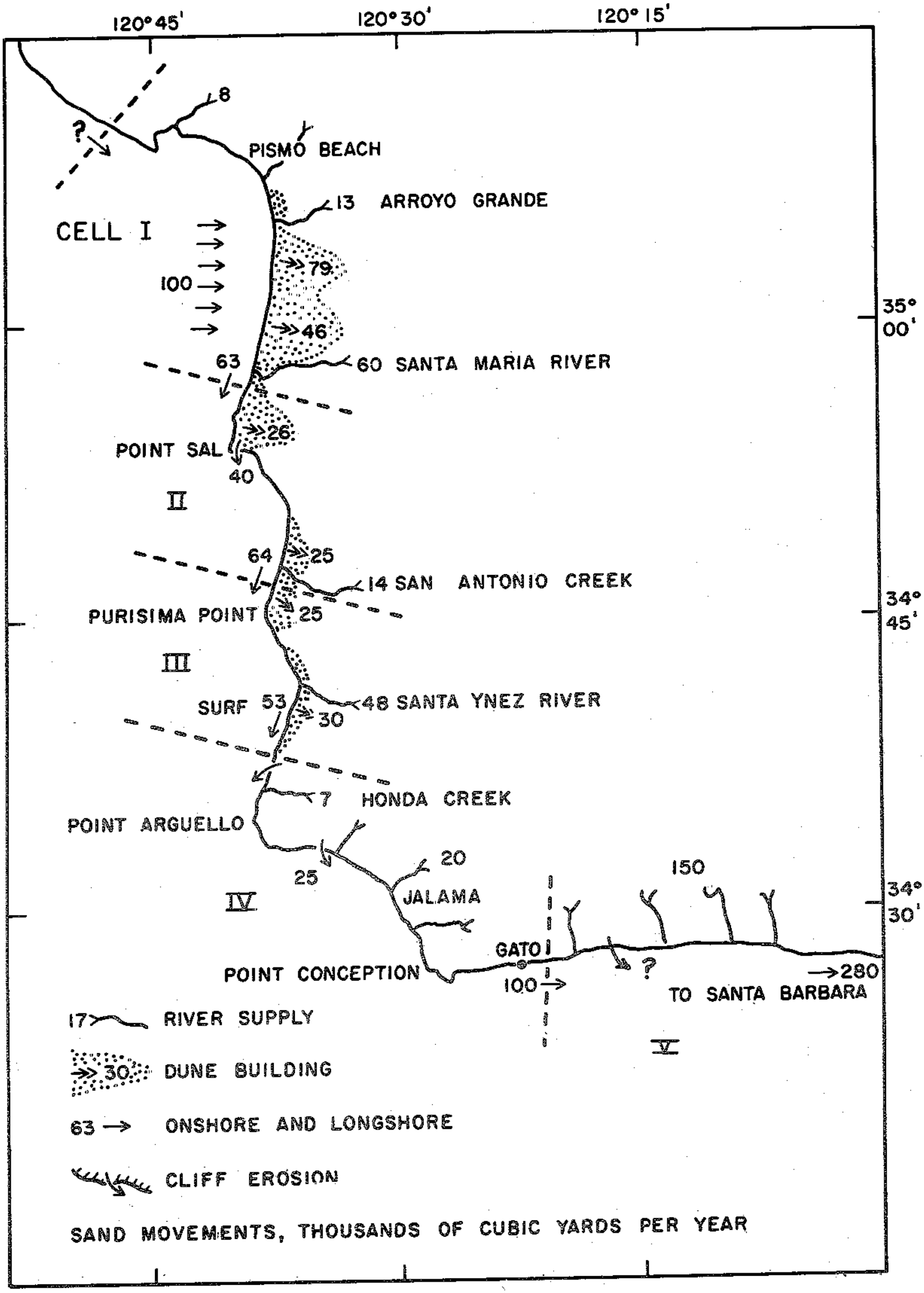

Figure 15. Schematic Diagram of the Budget of Littoral Sands

TABLE 1

Calculated Seasonal and Annual Longshore Components of Wave Energy (per Lineal Foot of Shoreline at each Location in Billions of ft-lbm per sec^2)*

	Winter (DJFM)	Transition (AMON)	Summer (JJAS)	Annual Total	Annual Net
Santa Maria River (St 4)					
Toward upcoast	24.6	13.3	17.6	55.5	16.1 toward
" downcoast	21.8	24.5	25.3	71.6	downcoast
San Antonio Creek (St 8)					
Toward upcoast	31.5	16.9	21.2	69.6	16.4 toward
" downcoast	25.5	28.7	31.8	86.0	downcoast
Surf (St 9)					
Toward upcoast	28.7	15.7	22.8	67.2	13.6 toward
" downcoast	24.3	27.3	29.2	80.8	downcoast
Gato (St 15)					
Toward upcoast	4.5	0.6	0.1	5.2	25.3 toward
" downcoast	10.7	6.8	13.6	31.1	downcoast

*Note that 1 ft-lbm/sec^3 = 1 ft-poundal/ft-sec = 1/32.2 ft-lbf/ft-sec, where lbf is pounds force.

TABLE 2

Estimate of the Longshore Transport of Sand Based on the Longshore Component of Wave Energy (Thousands of Cubic Yards)

	Winter (DJFM)	Transition (AMON)	Summer (JJAS)	Annual Total	Annual Net
Santa Maria River					
Toward upcoast	95	51	68	214	-
" downcoast	83	95	98	276	62
San Antonio Creek					
Toward upcoast	119	64	80	263	-
" downcoast	97	109	121	327	64
Surf					
Toward upcoast	109	59	86	254	-
" downcoast	92	103	112	307	53
Gato					
Toward upcoast	17	2	0.4	19.4	-
" downcoast	41	26	52	119	100

TABLE 3

Estimate of sand discharge from the Santa Ynez River during flood of 1958. Estimate is obtained by application of Colby's relation (Colby, 1964, Figure 19) (2) to water discharge measured at bridge near Lompoc (U. S. Geological Survey Gauge Station). After Lampietti, 1964 (20)

Date 1958	Mean Vel. FPS	Average Depth Feet*	Discharge of Sand Tons/Day/Ft of Width	Discharge of Sand Yd^3/Day
16 March	4.67	4.0	60	4,450
22 March	---	---	--	---
3 April	9.76	---	--	---
4 April	7.54	4.5	120	10,500
7 April	8.19	6.0	200	17,900
14 April	4.31	5.0	50	4,300

Total Discharge Estimate 1958

16 to 22 March $5 \times 4{,}450 = 22{,}000$

3 and 4 April $2 \times 10{,}500 = 21{,}000$

5 to 9 April $5 \times 18{,}000 = 90{,}000$

10 to 16 April $7 \times 4{,}300 = 30{,}000$

Total 163,000 yd^3

Say 160,000 yd^3

---

*Calculated from $\frac{\text{Discharge}}{\text{Velocity} \times \text{Width}}$

TABLE 4

Estimated Coastal Sand Discharge from Streams Between Pismo Beach and Santa Barbara

Stream	Drainage Area Mi^2	Sand Discharge Yd^3/Yr
San Luis Obispo Creek	85	8,000
Arroyo Grande	130	13,000
Santa Maria	630	60,000
San Antonio	140	14,000
Santa Ynez	480	48,000
Honda	10	7,000
Others, Point Conception to Gato	30	20,000
Others, Gato to Santa Barbara	210	150,000
	Total	320,000

TABLE 5

Estimate of the Sand Transport by Wind from the Beaches to the Dunes

Section of Coastline	Length Feet	Average Transport Rate* $Ft^3/Ft/Day$	Total Annual Transport Rate Yd^3/Yr
Pismo Beach Pier			
to	39,000	0.15	79,000
Oso Flaco Creek			
to	22,500	.15	46,000
Santa Maria River			
to	13,900	.15	26,000
Mussel Point			
Schuman Canyon			
to	37,000	.10**	50,000
Purisima Point			
Canada Tortuga Creek			
to	22,000	.10**	30,000
Bear Valley		Total	231,000

*Based on an angle of repose of 30°

**Assume 1/3 of area occupied by vegetation-covered ridges.

TABLE 6

MEDIAN DIAMETER (IN MICRONS) OF THE SEDIMENT SAMPLES

Sample numbers increase offshore and their position along the beach profile is indicated by "dot" in Figures 10, 11 and 12.

Sample	1	2	3	4	5	6	7	8	9	10	11	12	13
Profile													
1 N	150	147	146	160	149	160	154	147	142	143	112	88	49
2 N	165	154	157	171	170	191	138	146	130	113	90	77	
3 N	277	218	199	257	467	325	166	158	125	122	299	371	563
4 N	415	460	467	599	354	285	382	233	117	117	110	107	
5 N	354	344	377	373	384	448	376	302	259	128	125	444	717
6 N	319	306	268	248	238	270	190	248	233	129	116	95	106
7 N	283	238	227	268	218	319	199	155	151	130	83	98	
8 N	376	555	321	369	438	674	262	191	243	209	177	rock	rock
9 N	270	229	255	325	328	356	291	312	154	145	130	114	99
10 N	308	281	270	279	299	328	356	392	451	177	159	142	122
11 N	213	177	177	250	297	200	237	134	122	99	99		
12 N	238	247	183	202	177	190	157	149	134	177	933	rock	81
13 N	354	276	243	1223	163	164	167	137	134	123	109		
14 N	243	192	170	134	135	152	132	136	152	125	116	99	

TABLE 7

Budget of Littoral Sands in Thousands of Cubic Yards Per Year
(Refer to Figure 15)

	CELL I			CELL II			CELL III			CELL IV			CELL V		
	Pismo Beach to Santa Maria River			Santa Maria River to San Antonio Creek			San Antonio Creek to Surf			Surf to Gato			Gato to Santa Barbara		
Agency	In	Out	Net	In	Out	Net	In	Out	Net	In	Out	Net	In	Out	Net
River Transport	8 13 60		+81	14		+14	48		+48	7 20		+27	150		+150
Dune Building		79 46	-125		26 25	-51		25 30	-55	-	-	-	-	-	-
Cliff Erosion	-	-	-	40		+40	-	-	-	25		+25	some		
Longshore Transport	0?	63	-63	63	64	-1	64	53	+11	53	100	-47	100	280	-180
Total	81	188	-107	117	115	+2	112	108	+4	105	100	+5	250+	280	-30