WAR DEPARTMENT CORPS OF ENGINEERS, U. S. ARMY

BEACH EROSION BOARD
OFFICE OF THE CHIEF OF ENGINEERS

SHORE PROCESSES AND BEACH CHARACTERISTICS

TECHNICAL MEMORANDUM NO. 3

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AND BEACH CHARACTERISTICS

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FOREWORD

This report presents the results of a scientific study of some of the inter-relationships between the natural variables involved in beach phenomena. The work was done during the period, March to May 1942, under the sponsorship of the Beach Erosion Board, War Department, and the Department of Mechanical Engineering, University of California at Berkeley, by W. C. Krumbein, Senior Geologist. The author was holder of a John Simon Guggenheim Memorial Fellowship at that time.

Publication of the results was originally delayed by the war situation, but because of recent emphasis on beach information it is now desirable to make the results of the study available. It is felt that the method of approach employed as well as the factual data will be of value to those concerned with beaches and shore processes.

Washington, D. C.
May, 1944

W.C.K.

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NOTE FOR SECOND PRINTING

This paper was published with a restricted classification in May, 1944, as Engineering Notes No. 17, Military Intelligence Division, Office, Chief of Engineers, U. S. Army (Technical Memorandum No. 3, Beach Erosion Board).

Classification has been removed and the paper is now reprinted for the use of all interested sections of the general public.

September 1947

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SHORE PROCESSES AND BEACH CHARACTERISTICS

EXPERIMENTAL DESIGN FOR BEACH STUDIES

The study of shore processes in nature is complicated by the presence of a large number of mutually dependent variables, none of which is susceptible to control in the field. As a consequence it has been difficult to discern and largely impossible to specify the physical law or laws controlling the behavior of the environment. It is believed, however, that the study of a relatively simple natural situation by the "closed system" method familiar to the exact sciences will allow the discovery and specification of, at least, the principal fundamental relations governing the behavior of matter in the system.

By definition a closed system is one in which the boundary conditions and the total energy of the system are known, and in which the transformations of matter may be observed and measured. In the study of beach processes isolated bays most nearly satisfy the conditions for closed systems. An isolated bay may be considered as a particular combination of boundary conditions, matter, and energy. All three of these may be measured and expressed to a degree satisfactory for a first approximation to theory. Comparison of a number of bays affords a basis for evaluating boundary effects, so that principles established locally may be applied generally to beach phenomena.

The problem to be studied was then formulated as follows: given a bay with associated headlands, beach, and cliffs, to evaluate the physical processes which occur there. Beaches are composed of particles which must be derived from some source; the particles must be carried from the source to the point of deposition, and the agent which carries them must be energized in some manner or other. The source of the beach material is the adjacent terrain, which may be studied by geological methods. Energy is supplied by waves which strike the shore. The study of these waves, including their role in generating shore currents and carrying material, is a problem in earth physics. The interaction of matter and energy as it affects the land-forms developed (beaches, bars, spits, sea cliffs, etc.) may be studied by geological or geophysical methods; an evaluation of the processes in terms of beach stabilization and control is in the domain of engineering.

This analysis of the problem indicates the kinds of data to be obtained. These include (1) the characteristics of the waves in terms of height and period, as an index of the energy being supplied to the system; (2) the supply of beach and associated material, in terms of the amount available, as well as the size, shape, and other dynamical attributes of the particles; (3) specification of the erosional and depositional land-forms in the environment, and their relation to processes which form them and materials which compose them; (4) definition of the boundary conditions which control the distribution of wave energy in terms of refraction patterns, and which exert an effect on the materials and land-forms adjacent to the boundaries.

The present study is approach to this experimental design. Limitations arising partly from war conditions prevented the collection of complete data on each of the four factors involved. They are all touched upon, however, to frame the study within its larger background.

The coast of California is ideal from the closed system point of view, in that many of its beaches are found on relatively isolated portions of the coast, each bounded by headlands which to a large extent prevent the migration of matter or wave energy from one system to another. In choosing a bay and beaches for study it is desirable that the beaches be free from artificial structures and the bays represent a type, so that the results may be extended to similar bays. Halfmoon Bay satisfies both of these conditions. It is complicated by very few artificial structures, and in form it is typical of a number of other bays, including Drake Bay, Bolinas Bay, and San Pedro Bay.

By designing a study which repeats certain measurements at intervals, information regarding the stability of the beach in terms of width, slope, sand size, etc., may be obtained. The study should extend throughout at least a year to evaluate seasonal effects. At Halfmoon Bay the study was confined to the spring season, but data are available on winter and summer conditions from previous work by M. P. O'Brien (unpublished reports in Beach Erosion Board files).

THE PHYSICAL SETTING OF HALFMOON BAY

a. Topography and Hydrography. - Halfmoon Bay lies about 25 miles south of the Golden Gate. It is sheltered on the north by Pillar Point, which rises 181 feet above the sea, and on the south by Point Miramontes, 6.5 miles south-southeast of Pillar Point measured along the curving shore. The curvature of the shoreline is greatest at the northern end, gradually diminishing to the south, in the manner of a logarithmic spiral. The bay is bordered by a sandy beach which terminates against a sea cliff cut into loosely consolidated sand and gravel. Sand dunes occur locally along the shore. The bay is shown in figure 1.

Immediately east of Pillar Point is a belt of low land which extends northwestward toward Point Montara. Although this belt resembles a tidal slough filled with detritus, the San Mateo topographic map indicates that the surface rises to more than 50 feet above sea level within 1½ miles north of the bay. The sediments exposed in this trough are the same as the terrace materials to the east. This low land is therfore part of the general terrace which rims the bay. The surface of the terrace is gently tilted in a north-south direction along an east-west axis; it lies only a few feet above sea level at Pillar Point, but rises to some 60 feet above the sea at Point Miramontes. A gentle warp is superimposed upon the tilt, so that the height of the terrace varies somewhat along its extent, rising to its greatest height at Point Miramontes. The terrace merges inland with the range of hills which parallels the bay to the east and south.

Several small streams enter Halfmoon Bay from the north and east. The total drainage area of the bay is about 35 square miles, but no data are known to the writer on the total stream discharge.

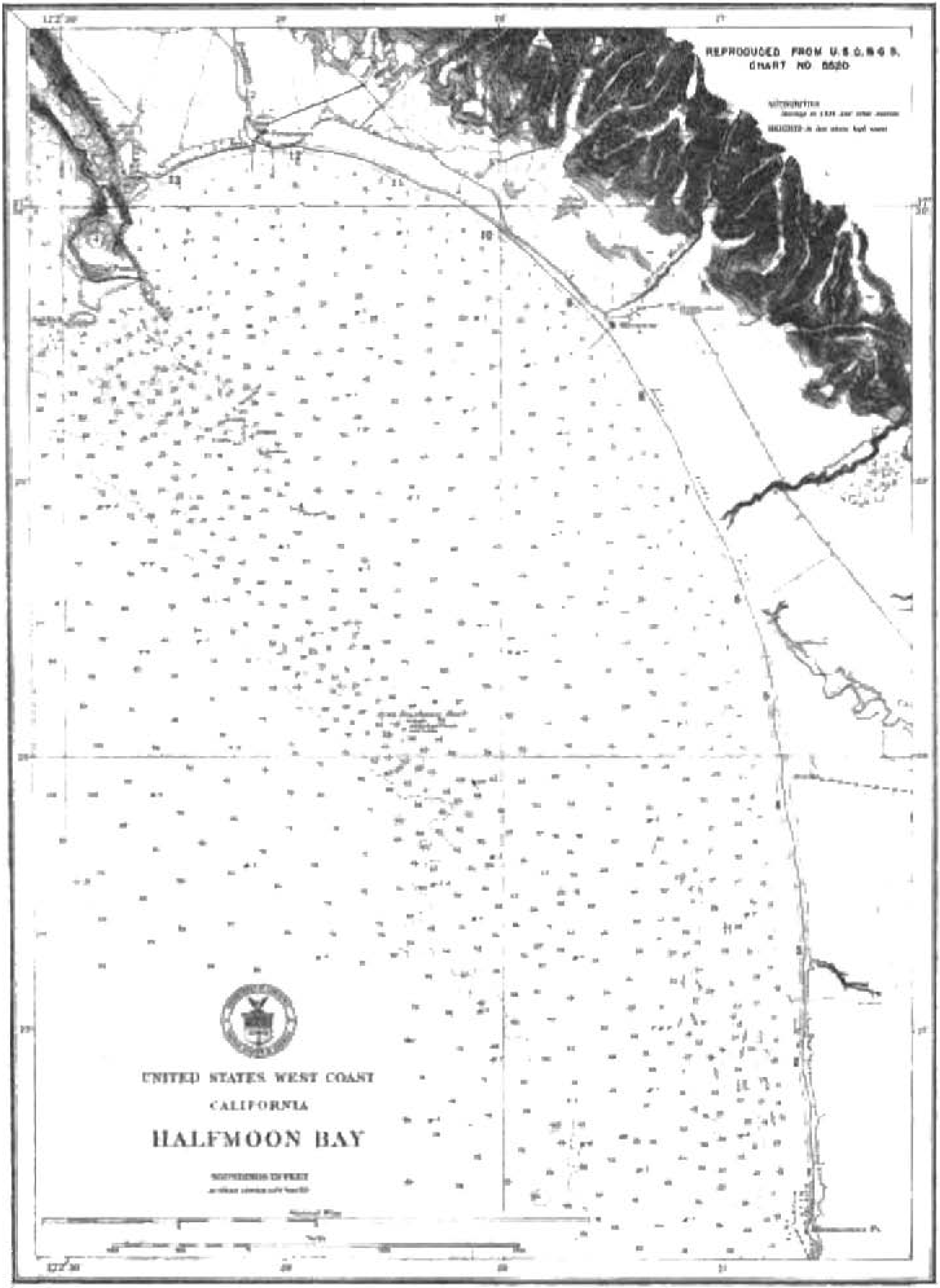
Halfmoon Bay deepens gradually with the regularity interrupted by two reefs which trend to the south-southeast from Pillar Point (see figures 1 and 2). The northern reef is just submerged at low tide and extends about a mile from the Point. The southeast reef has depths of about 20 feet over it at low tide. The greatest depth within the bay is about 10 fathoms, just east of the southeast reef. The bottom is generally sandy, although the trend of the reefs suggests that they are submarine extensions of the bedrock at Pillar Point.

b. Geology. - The terraces along Halfmoon Bay are composed of Pleistocene sand and gravel. The elevation of the terrace and the presence of sea cliffs attests to the relatively recent development of the bay. The large mass of Montara Mountain represents the oldest rock in the vicinity. Pillar Point, as well as the hills which lie to the east of the town of Halfmoon Bay, and an early marine terrace exposed at sea level at Point Miramontes, are all composed of Tertiary sediments. Figure 3 is a geological sketch map of the area.

The only formations which lie along the bay other than Pleistocene and recent deposits are the Purisima and Merced formations. The Purisima is of Miocene-Pliocene age. The particular beds which are exposed at Point Miramontes are dark gray to black fossiliferous shale, with a general northwest-southeast strike, and a moderate dip toward the northeast. The beds are truncated and the Pleistocene deposits rest unconformably upon them. The rocks of Pillar Point belong to the Merced formation, of late Pliocene age. They consist of marine conglomerate, sandstone, and shale, folded into a series of minor synclines and anticlines. The members vary in their resistance to erosion. The structural pattern of the rocks is revealed by recent cutting of Pillar Point.

The geological history of the bay area includes the intrusion of quartz diorite into ancient sedimentary rocks, probably during pre-Jurassic times. The Jurassic and Cretaceous periods left no rock records near the bay, but during this interval uplift and erosion exposed the quartz diorite at the surface. The Teritary is represented by several formations, which rest unconformably upon the older rocks. The Tertiary sediments are largely marine, and represent an inundation of the region by the sea. At the close of the Tertiary came a marked disturbance, in which the rocks were uplifted, folded, and faulted. Erosion developed marine terraces, a portion of which is exposed on the Purisima at Point Miramontes. Following truncation came depression of the coast, during which Pleistocene sand and gravel were deposited as an apron on the western slopes of the hills. This episode was followed by uplift, warping, and tilting. The present sea cliffs were cut into these elevated Pleistocene deposits, and the modern beach with its fringe of dunes was developed.

c. Meteorology and Oceanography. - The local wind rose shows that northwesterly winds prevail during April and May. At San Francisco winds blow from this direction 38 per cent of the time in April and 61 per cent of the time in May. Seaward of Halfmoon Bay the percentages are 20 and 32 for April and May respectively. These winds have an average force of


REPRODUCED FROM U.S.C.&G.S.
CHART NO 5520
UNITED STATES WEST COAST
CALIFORNIA
HALFMOON BAY
SOUNDINGS IN FEET
122° 30'
29'
28'
27'
37° 30'
29'
28'
27'
10
11
12
13

4 units on the Beaufort scale. Winds from the north blow less than 10 per cent of the time during both months at San Francisco, but seaward they occur 16 and 19 per cent of the time. The general prevalence of winds from a northwesterly direction is probably explained by a relatively permanent high-pressure area over the Pacific west of the Golden Gate.

The California current in the open sea to the west of the bay has a generally southerly direction, but according to Sverdrup (Oceanography for Meteorologists, p. 203) areas of upwelling north of the Golden Gate and south of Monterey Bay cause swirls during the Spring and early summer months. These swirls develop a northward current along the coast west of Halfmoon Bay. No data are given within the bay itself. The writer knows of no specific data on waves in the open sea along the coast from the Golden Gate to Santa Cruz. Wave observations were made within the bay during this study; the results are given later.

The tidal cycle in Halfmoon Bay occurs about an hour earlier than at the Golden Gate. The tides are mixed with the long runout following higher high water; the high water interval is 10 hours 30 minutes. The mean range of the tide is 3.8 feet and the diurnal range is 5.5 feet.

OBSERVATIONAL DATA

The present study extended from 4 March to 9 May 1942. The beach was visited each Saturday and except for the first reconnaissance visit, a systematic plan was followed in obtaining data on each visit. Stakes were set along the base of the sea cliff at approximately half mile intervals and numbered 1 to 13 from south to north. The location of these stations is shown on figure 1, and a description is given in table 1. All stations were not visited each Saturday, but an alternation was followed so that about 10 sets of observations were made each time within the tidal limits.

a. The State of the Beach. - The western side of Pillar Point is bordered by numerous reefs. The eastern side is fringed with reefs at its southern end, but develops into a cobble beach to the north. A rock spur separates this pocket beach from the main strand to the east. The spur essentially prevents the migration of cobbles to the east, although some of the fine sand from the bay shore has moved westward. East of the spur a sand beach extends uninterrupted nearly to Point Miramontes. Rock reefs appear at low tide about a mile north of the point and become more prominent to the south. At Point Miramontes itself a continuous reef extends outward from the sea cliff. In this vicinity the sand beach becomes discontinuous and patchy.

The width of the beach varies from one end of the bay to the other. On 11 April 1942 it was 250 feet wide east of Pillar Point and diminished somewhat irregularly to 140 feet wide north of Point Miramontes. During subsequent visits the beach widened to some extent along its entire course.

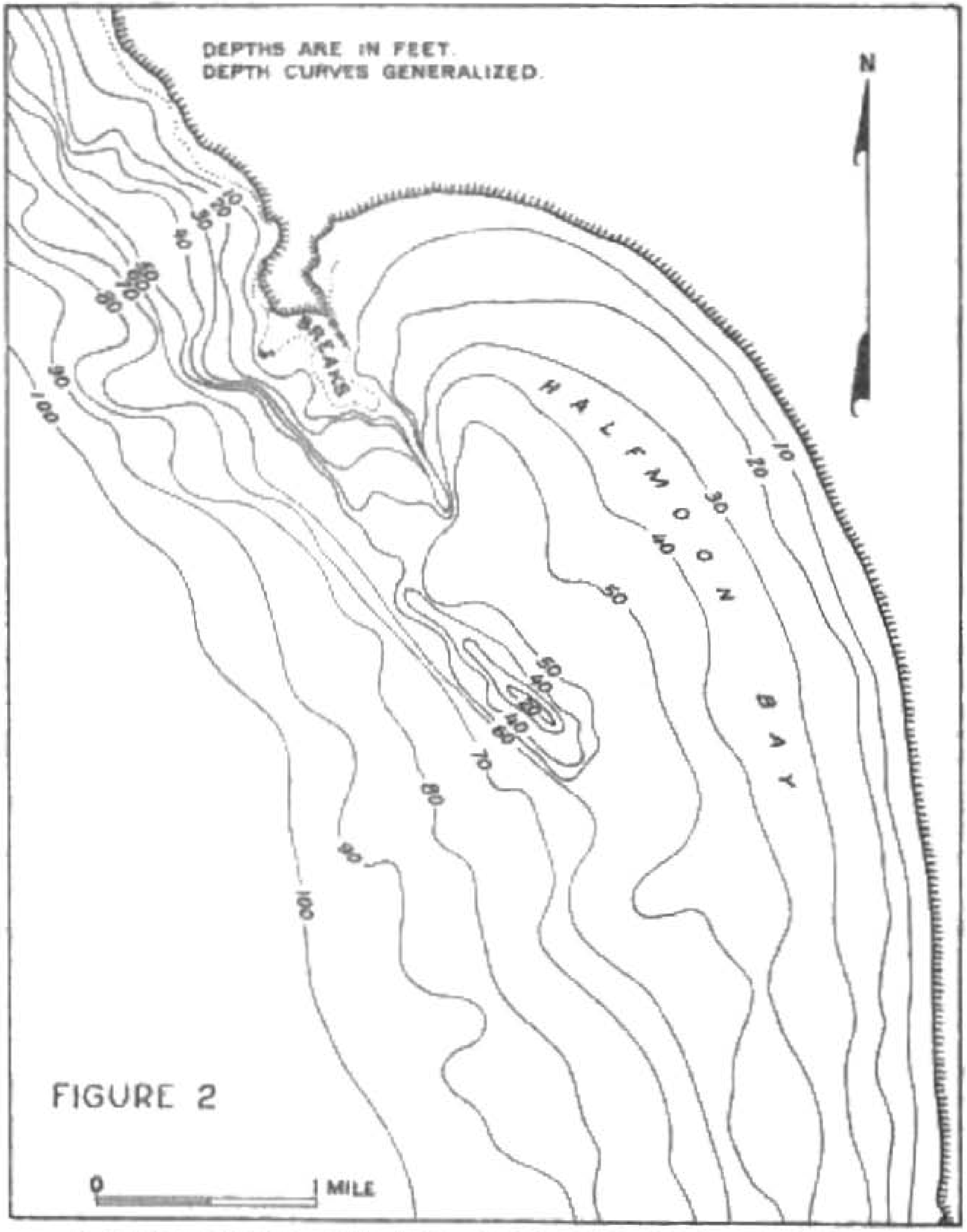
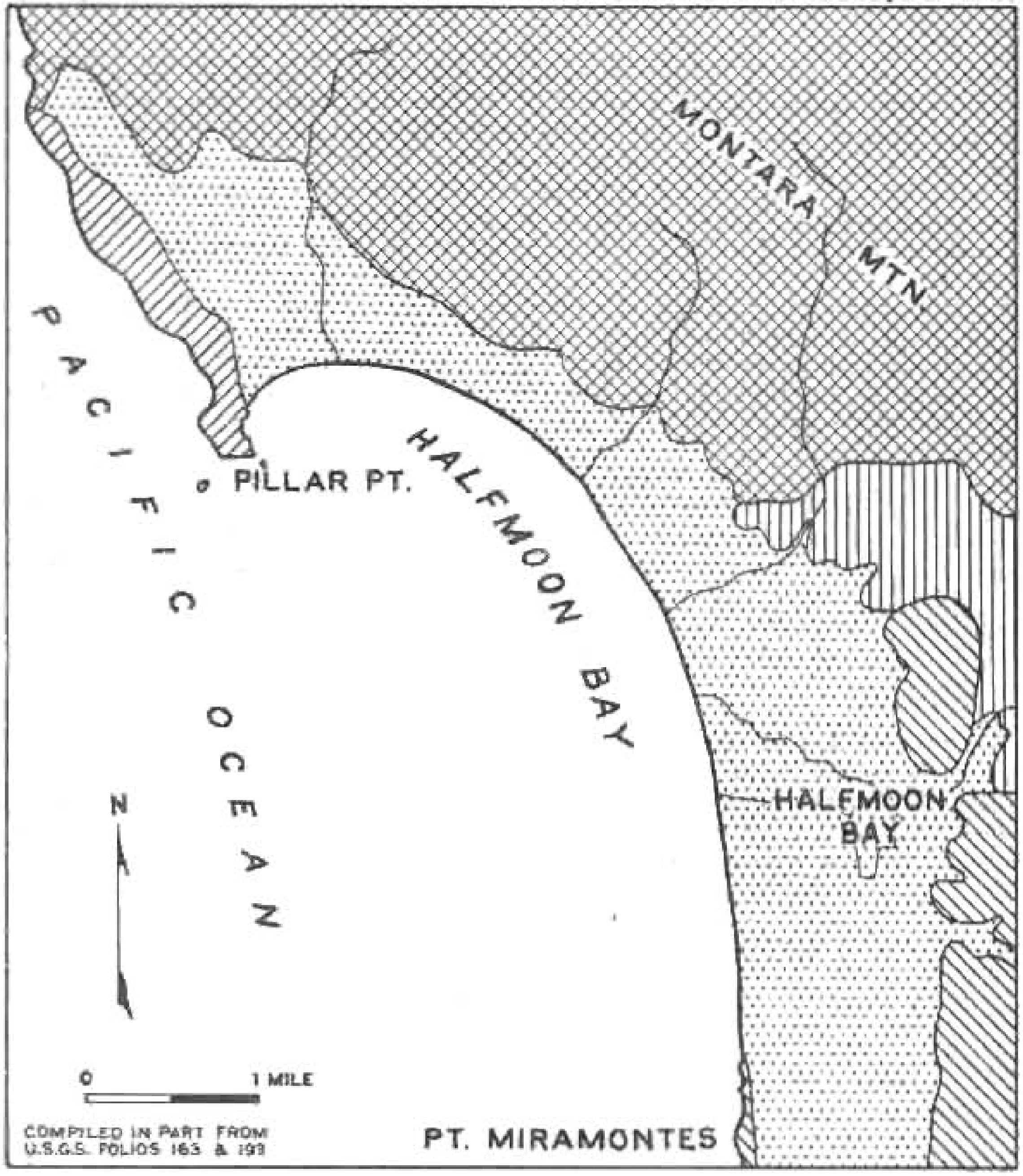


FIGURE 2

SUBMARINE RELIEF - HALFMOON BAY, CALIF.
(0 - 100 FT. ONLY)



░ TERRACE, DUNES, BEACH (QUATERNARY)

▨ MERCED FORMATION (TERTIARY)

▧ PURISIMA FORMATION (TERTIARY)

▥ VAQUEROS SANDSTONE (TERTIARY)

▦ QUARTZ DIORITE (PRE-JURASSIC ?)

FIGURE 3

AREAL GEOLOGY OF HALFMOON BAY AND VICINITY

Erosion is active at Point Miramontes and north to station 3, a distance of about 1 mile. Slumped portions of the cliff are common along the beach. Beyond station 3 the cliff is protected by a well developed berm, which is present continuously to station 9 just north of Miramar. Beyond station 9 the foreshore extends to the base of the sea cliff, which is awash at high tide. Erosion becomes prominent again at station 11 and continues to Princeton, where extensive cutting is evident.

Several areas of dune sand fringe the beach between stations 4 and 8. These dunes are best developed in the vicinity of station 7, but nowhere do they extend inland farther than a few hundred feet beyond the beach. Plate I includes several photographs of the beach showing the varying character of the beach along its extent.

b. Profiles and Beach Slopes. - Ten beach profiles were measured on April 11. They were located along the crests of beach cusps wherever the latter were present. The profiles are shown in figure 4; they indicate a decreasing slope of the foreshore from south to north and show a well developed berm from stations 3 to 9. A trace of an earlier berm was found at station 12, protected by a re-entrant into the sea cliff. The points marked "S" indicate sand samples taken at the time the profiles were measured.

The berm on April 11 appeared to be largely the result of the previous winter's wave conditions. The height of the berm above MLLW averaged 12.7 feet; the individual values are shown in table 2. It is interesting to note that O'Brien's observations in 1930 indicated an average elevation of 13 feet for the previous winter's berm.

Table 2
Elevation of Berm above MLLW, 11 April 1942

Station	Berm Elevation, feet
1	Not present
3	16
4	13
6	11
7	14
8	12
9	13
10	Not present
11	Not present
12	10 (Trace only)
13	Not present

Limitations of time prevented the measurement of complete beach profiles at later dates, but beach slopes were measured during each visit with a Brunton hand compass. The complete data are shown in figure 5, arranged according to dates. O'Brien's observations of June 1930 are included. Despite the scatter of the individual points there is a definite trend to the data. The position of O'Brien's points within the scatter suggests that the slope relations of the beach have not changed significantly within the last 12 years.

Table 1

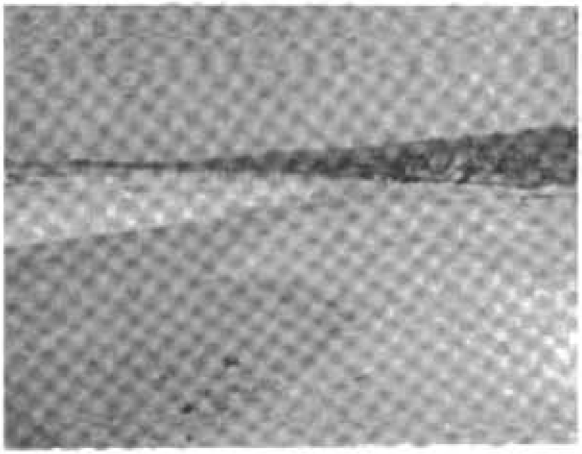
Description of Stations along Halfmoon Bay

Station	Miles from Pt. Miramontes	General Remarks
1	0.25	Rock reefs abundant, sand very coarse, beach fairly narrow, cliffs 60 feet high, erosion evident.
2	0.80	Occasional rock reefs, sand coarse, cliffs 50-60 feet high, erosion evident.
3	1.20	Well developed berm, cliffs 40 feet high.
4	1.80	Well developed berm, cliffs 20 feet high.
5	2.20	Well developed berm, sand moderately coarse, sand dunes on terrace.
6	2.60	Berm present, stream parallels cliff inland of beach. Cliff 15 feet high.
7	3.20	Well developed berm, prominent dune belt parallels wide beach.
8	3.70	Well developed berm, dune belt ends just north of station.
9	4.10	Partially eroded berm, wide beach, sand moderately fine. Cliffs 10 feet high.
10	4.50	No berm present, wide beach, sand rather fine. Some erosion evident. Cliffs 10 feet high.
11	5.10	No berm present, active erosion along cliffs which are 20 feet high.
12	5.50	Small trace of berm in re-entrant. Wide beach, very fine dark sand. Very active erosion along cliffs which are 15 feet high.
13	6.10	No berm present. Very wide beach, very fine dark sand, always moist. Cliff here about 1 - 2 feet high.

North from Station 1, showing rock reefs.
High tide, April 4, 1942.

North from Station 3, showing old cusps.
May 2, 1942.

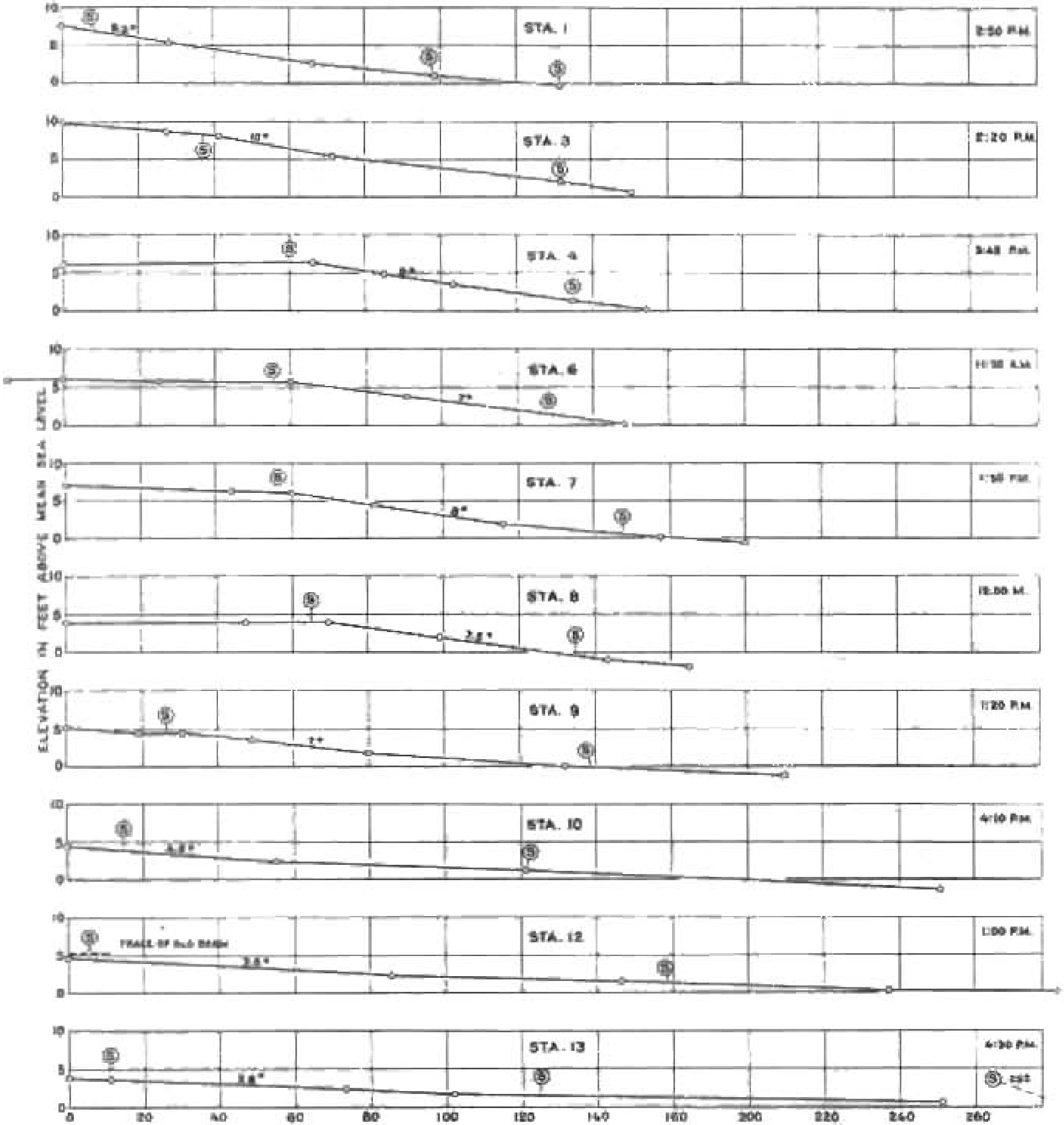
North toward Station 7, showing well
developed berm. April 18, 1942.



North from Station 8, toward pier at
Kirmmar. Note cusp in foreground.
April 18, 1942.

View north from Station 11. Note absence
of berm and recent erosion. May 2, 1942.

PLATE I



SAMPLING STATIONS SHOWN THUS Ⓢ

HALFMOON BAY. CALIF

BEACH PROFILES

APRIL 11, 1942

FIGURE 4

Table 3

Observations on Beach Cusps

Date 1942	Station	Number Measured	Average length feet	Standard Deviation per cent	Remarks
4/11	1	11	147	16.7	
"	3	13	199	22.0	Winter cusps?
"	4	13	164	25.9	
"	6	5	148	9.5	
"	7	8	159	4.9	
"	8	10	148	17.1	
"	9	6	175	3.4	Winter cusps
4/18	2-3	11	222	15.4	Winter cusps?
"	4	10	182	15.5	
"	5	9	175	21.6	
"	7	8	174	5.0	
"	8	13	152	23.1	
"	9	6	175	3.4	Same as before
4/25	2-3	11	208	27.0	Storm cusps?
"	4				Old cusps eroded
"	5				Old cusps eroded
"	7	4	126		4 old cusps
"	8				No cusps at all
5/2	2	11	149	18.2	
"	3	12	143	22.2	Also 6 old cusps
"	5-6	10	147	9.0	
"	8	10	153	15.8	

c. Beach Cusps. - Measurements and observations on cusps were made during each visit to Halfmoon Bay. The number of cusps, their average length, and the standard deviation of length for each station are given in table 3. Standard deviation is a measure of the average scatter of a series of observations about their mean value. Formulas for the calculation of the standard deviation are given in all statistics texts.

On April 11 cusps were well developed and apparently continuous from stations 1 to 9. A moderate sea was running, with waves approaching the bay from the southwest. On April 18 conditions had changed. A southwest storm occurred during the week, and some of the previous cusps were partly eroded; elsewhere entirely new cusps had formed. A striking feature of some of the cusps, especially near station 3, was their asymmetry. The crest lines trended northward of the normal by as much as 32°. The asymmetry was not completely systematic, however, because undistorted crests occurred among them.

On April 25 the aspect of the cusps had nearly completely changed. In the south a new set of shorter cusps was present, with traces of the earlier cusps on a higher berm. At station 5 the old cusps had been completely cut away, and a sea cliff 5 feet high had been cut into the berm. At station 7 new cusps were faintly discernible, but at station 8 no trace of cusps was found. By May 2 the newer cusps were well developed as far north as station 8. The cliff at station 5 was still prominent, and no new cusps had formed there. On May 9 the sea was relatively calm, with waves approaching the bay from the northwest, and cusps were well developed.

The observations suggest that cusps formed during the winter and early spring are longer and are associated with higher berms than those formed in late spring and summer. The writer assembled all available data, including O'Brien's 1930 observations, and made a tentative classification of the cusps into two main groups, with a possible intermediate group. The results are shown in figure 6. The upper series of points includes long cusps formed during winter or during spring storms. The lowermost line represents short cusps formed in summer or during quiet conditions in the spring. Between the two sets are scattered points which represent a transition between the extremes. If the classification is sound, it suggests two things: (1) cusp length is a function of the average wave and tidal conditions which prevail at the time of their formation, and (2) cusp length within any series decreases systematically from south to north along the beach. The writer is not prepared at present to discuss theories of cusp formation in terms of wave periods, lengths, or heights. Apparently cusps represent a steady state condition along the shore; although abrupt changes in conditions may destroy old cusps by erosion, new ones begin to form almost simultaneously and remain relatively constant in size and form as long as the new conditions prevail. It is observed that cusps are present only where a berm occurs along the beach. The seaward edge of the berm is serrated, but the low water line is nearly straight. The cusps are therfore marginal land-forms associated with the berm.

An oft-mentioned feature of cusps is their regularity in length. When detailed measurements are made, however, it is found that occasionally

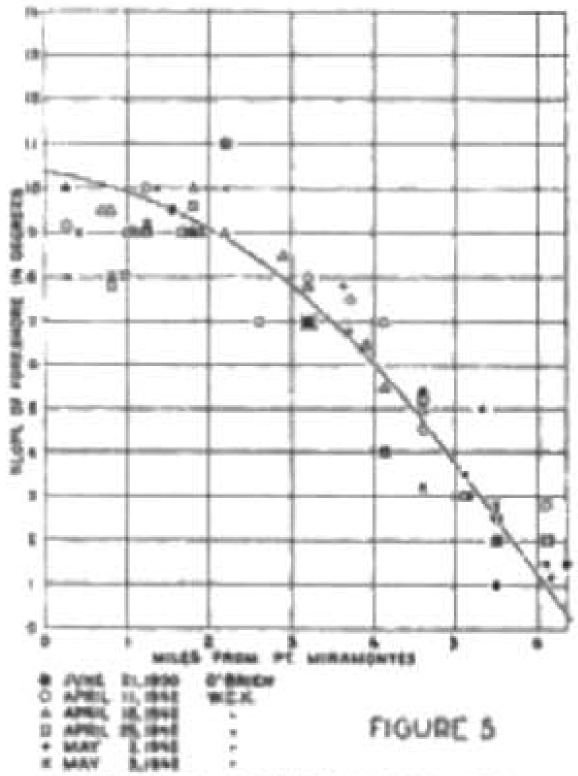


FIGURE 5

OBSERVED RELATION BETWEEN FORESHORE SLOPE AND DISTANCE

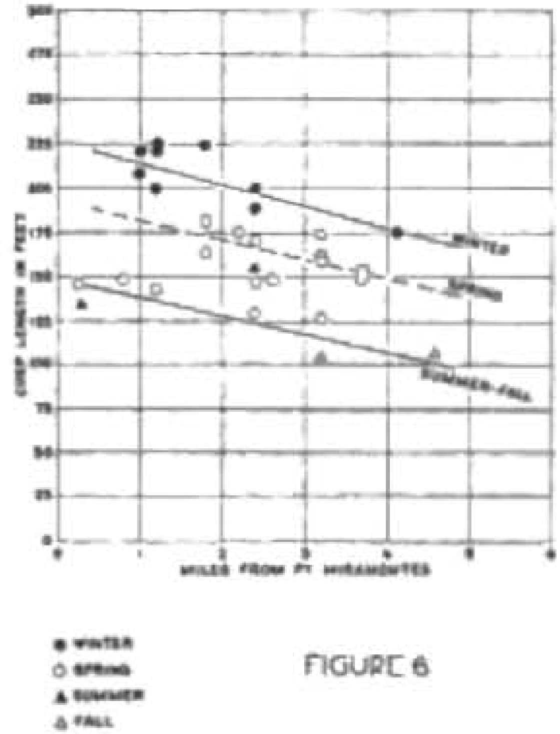


FIGURE 6

PROBABLE SEASONAL VARIATIONS OF CUSP LENGTH AND DISTANCE

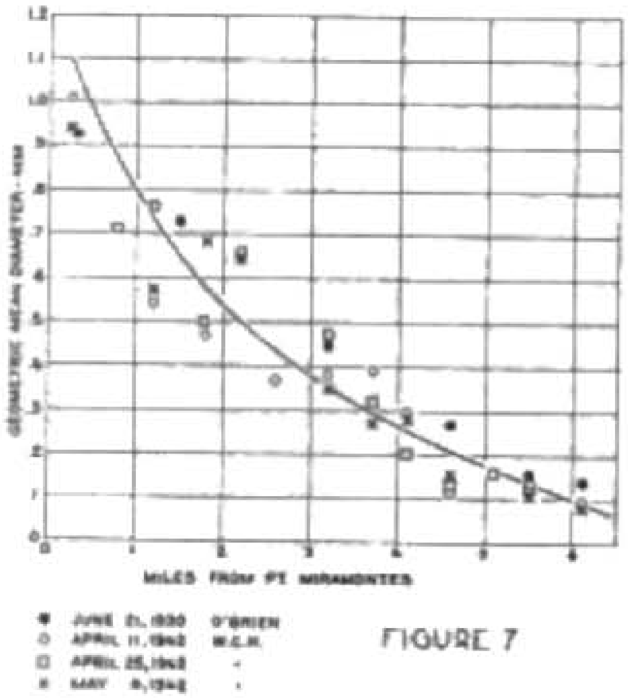


FIGURE 7

OBSERVED RELATION BETWEEN SAND SIZE AND DISTANCE OF MEAN SEA LEVEL SAMPLES

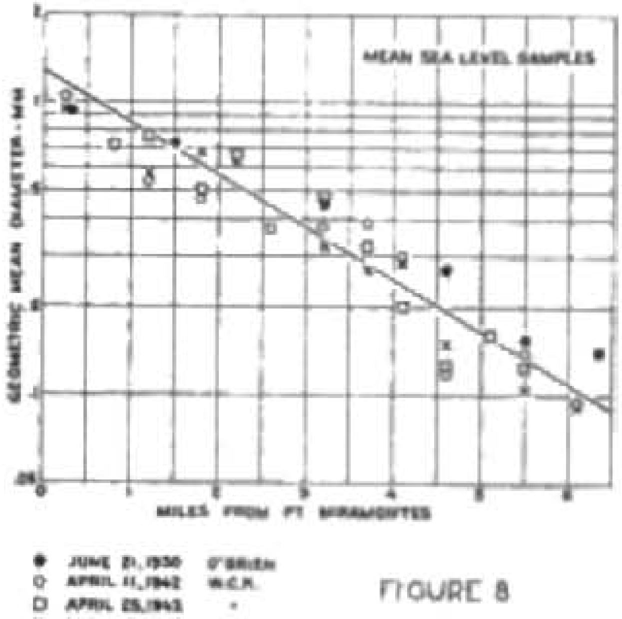


FIGURE 8

OBSERVED RELATION BETWEEN SAND SIZE AND DISTANCE OF MEAN SEA LEVEL SAMPLES

(SEMI-LOG PLOT OF FIGURE 7)

an unusually long or short cusp occurs within a series. The effect of these irregularities is that the standard deviation of length is larger than expected. In the present instance the average standard deviation of all cusps is of the order of 15 per cent of their length, but this value varies along the beach, as table 4 indicates.

Table 4

Variation in Standard Deviation of Cusp Length

Stations	Standard Deviation
1,2,3	20 per cent
4,5,6	16 " "
7,8,9	11 " "

Thus the variability of the cusps diminishes to the north, perhaps as a function of the degree of shelter from direct wave attack afforded by Pillar Point and its associated reefs.

d. Sand Samples and the Properties of Sediments. - Sand samples were collected at low water, mean water, and high water levels, and from the crest of the berm. All samples were taken from the crest lines of beach cusps, wherever the latter were present. Sampling was repeated at intervals, especially from mean water level, which was sampled on April 11, 25, and May 9.

The sand samples were taken to a depth of one foot, in order to average out nonsystematic variations. They were quartered in the field, and in the laboratory they were washed, dried, and sieved.

The present report includes only the size data of the samples, but other attributes may be equally significant. Work with sediments has shown that six particle properties are important. These are size, shape (sphericity), roundness, mineral composition (density), surface texture, and particle orientation. In addition, sediments have various megascopic mass properties, as porosity, permeability, compactibility, etc. The treatment of the size data in the present discussion is an example of the attack which may be made on each particle property.

The particle attributes may be used in interpreting dynamical processes. Two such processes are selective transportation (sorting action) and particle abrasion. Sorting action is largely a function of settling velocity, and expresses itself in terms of size, shape, and density. Abrasion, on the other hand, changes the roundness and surface texture of the particles most markedly. Particle orientation (the arrangement of the particles within the deposit) appears to reflect the particular conditions under which deposition occurs.

The size data of the samples were expressed as weight frequency percentages, and plotted as cumulative curves on probability paper. The use of probability paper permits the graphical determination of the median diameter, the geometric mean diameter, and the logarithmic standard deviation. The geometric mean diameter will be used in the following discussion. It is related to the center of gravity of the logarithmic size distribution, and is stated by House to be the most significant average for dynamical studies of particles.

Figure 7 shows the geometric mean diameter of all mean water level samples plotted as a function of distance along the beach. O'Brien's 1930 data are included. A negative exponential function is suggested, which is shown by the semi-log plot of figure 8. The agreement with the straight line is satisfactory and indicates that the functional relationship is of the form

$$r = r_0 e^{-ax} \quad . \; . \; . \; . \quad (1)$$

where r is the size of any point x along the beach, r_0 is the initial size at $x = 0$, and a is the coefficient of size decrease.

One of the questions which arose in the present study was the extent to which repeated samples would give the same size data. This was answered by plotting each set of samples separately on semi-log paper, and determining the parameters of the straight lines. These are the initial size r_0, and the coefficient a of equation 1.

Table 5

Size Parameters of Mean Water Level Samples

Date	Initial size, r_0	Coefficient a
6/12/30	1.18 mm.	0.35 (1/mile)
4/11/42	1.18	0.41
4/24/42	1.19	0.42
5/ 9/42	1.30	0.45

The variation shown by these figures is within the range of scatter of any one set of data, and indicates that on the whole any single set of samples affords a good approximation to the trend, although any one sample may show considerable differences.

The samples collected from other levels were also plotted on semi-log paper, as shown in figures 9 and 10. The parameters (including the average of the mean water set) are given in table 6. The systematic increase in the value of r_0 in the table indicates that average size increases downslope normal to the beach. The systematic increase in the coefficient a indicates that the lower samples have a relatively greater rate of size decrease along the beach.

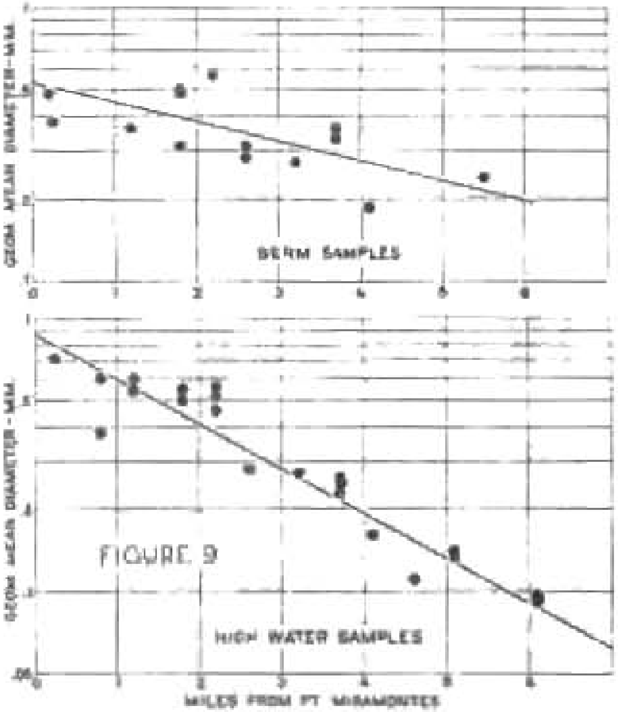


FIGURE 9

OBSERVED VARIATION OF SAND SIZE WITH DISTANCE FOR BERM AND HIGH WATER SAMPLES

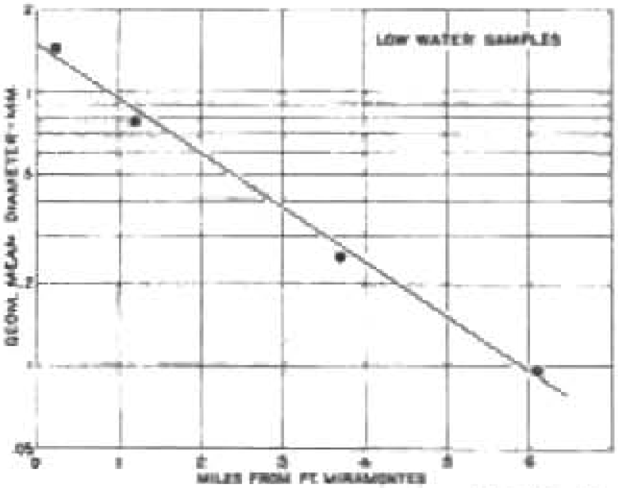


FIGURE 10

OBSERVED RELATION BETWEEN SAND SIZE AND DISTANCE OF LOW WATER SAMPLES

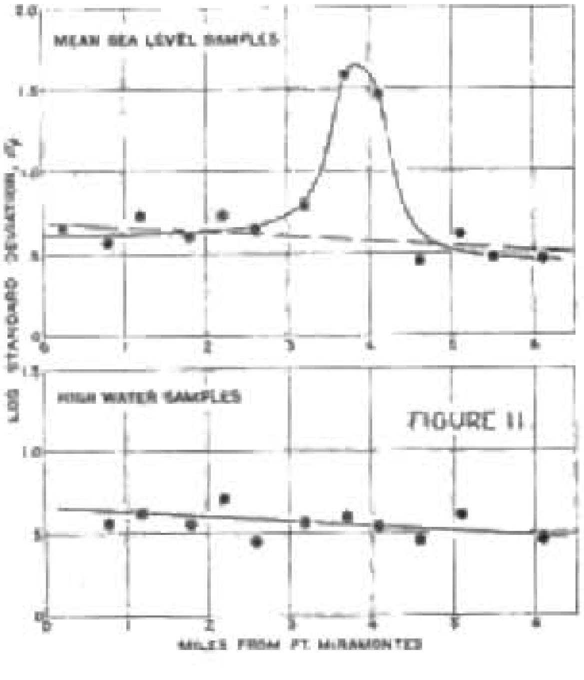
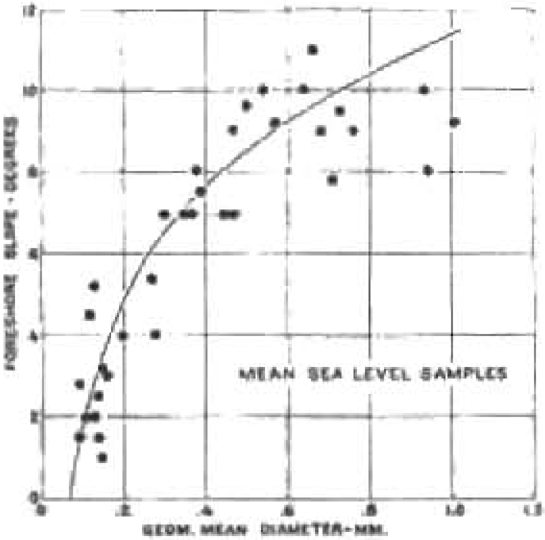


FIGURE 11

OBSERVED VARIATION OF SAND SORTING WITH DISTANCE FOR MEAN SEA LEVEL AND HIGH WATER SAMPLES



OBSERVED RELATION BETWEEN FORESHORE AND SAND SIZE FOR MEAN SEA LEVEL SAMPLES

FIGURE 12

Table 6

Size Parameters of all Samples

Samples	Initial size, r_o	Coefficient a
Berm	0.84 mm.	0.17 (1/mile)
High water level	0.88	0.39
Mean water level	1.25	0.41
Low water level	1.50	0.45

The logarithmic standard deviation, σ_ϕ , is a measure of the spread of the size frequency curve about the mean diameter. Large values indicate poor sorting, because σ_ϕ increases with increasing spread of the curves. There is a wide scatter of the individual values of σ_ϕ in the mean water level samples. However, when the data of any one set of samples is averaged, trends appear. Two of these are shown in figure 11. The upper graph represents mean water samples, and shows a marked maximum (representing poorer sorting) at stations 8 and 9. It was observed during sampling that very coarse material occurred beneath several inches of finer sand at the surface. This downward coarsening was encountered on all three sampling occasions. The large value of σ_ϕ apparently arises from a mixture of two size distributions in the samples. The lower material may represent a coarse layer from the winter beach, now exposed at low water.

The lower graph of figure 11 represents the high water sand samples. The absence of the maximum at stations 8 and 9 suggests that the coarse layer has been covered to a greater depth by the spring beach accretion. The straight line in the graph indicates a gradual improvement in sorting from south to north. The parallelism of this line with the dashed line in the upper figure indicates that the general change in sorting is the same for both levels of samples, if the lag effect is discounted. The relation in the lower graph is typical of many beach sands. Generally the sorting improves in the direction in which size decreases, which is the case here.

e. Relation between Sand Size and Beach Slope. - Figure 12 shows beach slope plotted against the corresponding geometric mean diameter of the mean water level samples collected at the time the slope was measured. The data show a distinct trend, and the finite abcissa at zero slope suggests a positive exponential function. This is shown in figure 13; the fair agreement with the straight line suggests that the function holds at least to a first approximation. From the graph,

$$r = R_o e^{bS} \quad . \; . \; . \; . \; (2)$$

Here r is the size associated with any slope of S degrees; R_o is the initial size for $S = 0$; and b is a coefficient of size increase. If size is taken as the independent variable the function becomes logarithmic:

$$S = (1/b) \log_e(R_o) \quad . \; . \; . \; . \; (3)$$

Equations 1 and 2 may be used to examine the relation between slope and distance, which was illustrated in figure 5. Those data fail to yield a straight line on either double log or semi-log paper. However, by eliminating r between the two equations, S may be found as a function of x:

$$R_0 e^{bS} = r_0 e^{-ax}$$

$$S = -(a/b)x + (1/b)\log_e(r_0/R_0) \quad . \; . \; . \; . \quad (4)$$

The predicted relation is linear, in which $-(a/b)$ is the slope, and $(1/b)\log_e(r_0/R_0)$ is the y-intercept. The numerical values of the several constants may be read from figures 8 and 13.

Table 7

Constants from Figures 8 and 13

$r_0 = 1.25$ mm.

$R_0 = 0.07$ mm.

$a = 0.41$ (1/mile)

$b = 0.23$ (1/mile)

Substituting these values in equation 4, we obtain:

$$S = -1.78x + 12.52$$

The coefficient of x represents the tangent of nearly 61°. The predicted line is shown in figure 14, which is figure 5 redrawn with equal scale units for degrees and miles. The agreement is excellent beyond about the first mile from Point Miramontes. The lower slopes in the initial parts of the beach can be explained as being due in part to boundary conditions. Rock reefs in this stretch, extending outward from shore, act partly as groins, with the result that the normal beach slope is reduced in their vicinity.

f. Waves and Currents. - The waves in Halfmoon Bay are much larger at Point Miramontes than near Pillar Point. This situation is illustrated in Plate II. A visual device was used to measure the relative wave heights from shore. It consisted of a slot cut into a sheet of closely-ruled graph paper, which was held at a fixed distance in front of the eye, and the wave height at the plunge point was measured on the scale. The first measurements were made with some skepticism, but after it was found that rather consistent results were obtained, a systematic series of reading was made. Table 8 includes all the data, based on averages of twelve wave heights at each station. The average wave periods were also indicated.

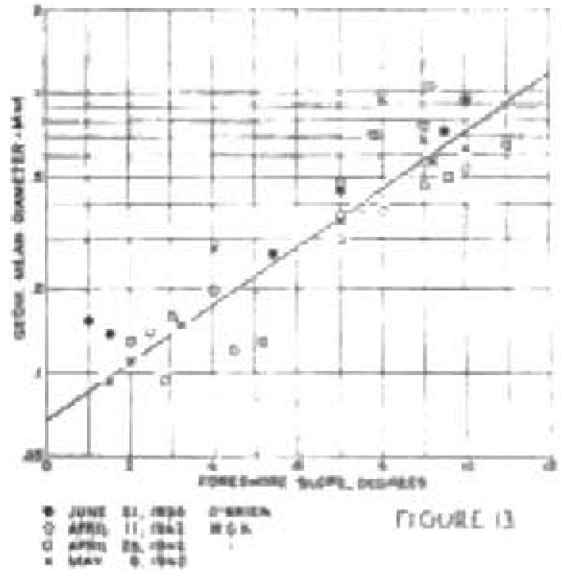


FIGURE 13

OBSERVED RELATION BETWEEN SAND SIZE AND FORESHORE SLOPE

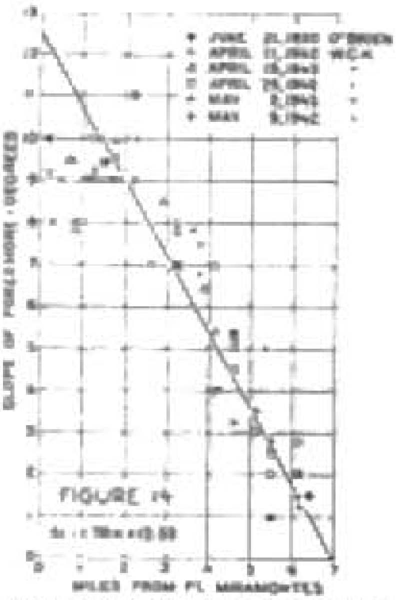


FIGURE 14

PREDICTED RELATION BETWEEN FORESHORE SLOPE (S) AND DISTANCE (x)

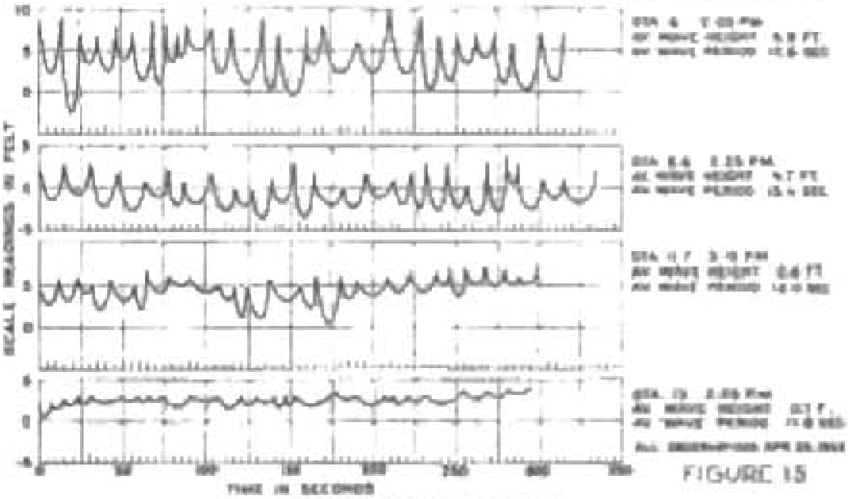


FIGURE 15

WAVE OBSERVATIONS

FIGURE 16

OBSERVED VARIATIONS OF WAVE HEIGHTS ALONG BAY SHORE

Observations were also made on April 25 from a boat anchored offshore. The depth of water at the wave crest and trough, and the time of passage of the crests were recorded for 25 successive waves. The sea was relatively rough, but four sets of satisfactory data were obtained. The average height and period were determined for each station, and the plotted curves of figure 15 show the results.

During the observations waves approached the bay from the northwest, and a fresh northwest breeze was blowing. Wave measurements on shore the same day yielded periods shorter than from the boat, but this is attributed in part to the running surf, which rendered it difficult to sort out the individual periods.

The combined wave data, including both shore and boat observations, are shown in figure 16. The arbitrary scales of height were converted to their numerical equivalent of approximately 1 unit = 1.5 feet. The wave height at Point Miramontes was of the order of 7 feet at the plunge point. Each set of observations is indicated separately on the graph. In each instance (except possibly on April 18) the waves approached the bay from the northwest, but the effects of refraction were such that the waves appeared to be essentially normal at all points along the shore. The weather was much milder on May 9 and the wave height was less, but the curve has the same general trend as the others.

Table 8

Wave Heights and Periods

Station	Data	4/18/42	4/25/42	5/2/42	5/9/42
1	Height*				3.50
	Period**				10.4
2	Height	4.10	4.30	4.16	
	Period	9.0	10.6	12.5	
3	Height	4.06	4.12	4.38	3.50
	Period	9.5	10.7	12.8	11.5
4	Height	4.10	3.64		
	Period	9.8	9.5		
5	Height	3.80	3.88	4.18	3.42
	Period	8.8	10.4	10.7	10.1
7	Height	3.50	3.58		-
	Period	9.9	9.7		12.5
8	Height			3.11	2.58
	Period			11.1	11.8
9	Height	3.04	2.68		
	Period	8.7	-		

Station	Data	4/18/42	4/25/42	5/2/42	5/9/42
10	Height	2.62	2.46	2.70	
	Period	-	-	-	
11	Height		2.04		
	Period		9.9		
12	Height	1.96		2.00	1.57
	Period	9.2		11.9	11.6
13	Height	1.50			1.05
	Period	9.3			11.4

* Arbitrary scale units. 1 unit = approximately 1.5 feet.
** Periods in seconds.

NB- Boat data are summarized in figure 16.

The boat data were transformed to the shoreline scale by adjusting the observed height at station 6 with the shore observations. The remaining points were plotted according to the ratio thus obtained, and are shown as black circles on the graph. The agreement between boat and shore data is fair; the steeper slope of the boat data may be a result of the necessity for anchoring the boat in fairly deep water to avoid surf, so that the waves were not always at corresponding points in their approach to the shore.

The average period of all waves observed during this study is of the order of 11 seconds. This corresponds to an average wave length of 620 feet in deep water.

Observations on currents and beach drift were much less satisfactory than wave observations. No equipment or colored dyes were used. What little data were obtained were contradictory, with marked reversals of direction due partly to conflicting currents set up by the beach cusps. O'Brien's 1930 report indicates a similar situation, with currents reversing their direction abruptly, or leaving the shore at an angle. On May 9, at station 6, a strong southward current along a shallow bar was found to run at 2.5 feet per second. Converstaions with local fishermen indicated a complex current system, which varies with the season and the weather. One believed that the strongest currents were toward the north, due to winter storms, but that drift was to the south in quieter weather. Another was of the opinion that circulation within the bay centered about stations 5 and 6, because driftwood tends to collect along this stretch of the beach. It is possible that currents in the open sea to the west may generate slow eddies within the bay, which in turn are modified by local winds and waves.

Indirect evidence of the direction of shore drift is obtained from the beach material itself. The average sand size decreases markedly to the north, and the sorting improves to the north. This suggests drift of the sand from Point Miramontes to Pillar Point. Fine sand is common in the pebbly pocket beach west of the rock spur at Pillar Point, but very seldom are pebbles found to the east of the spur. This also suggests a predominant drift from south to north.

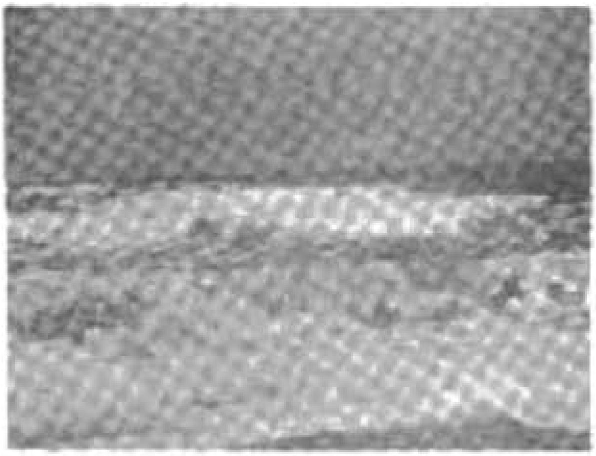
A sand pit was formerly operated at the mouth of Pilarcitos Creek. Operations began about the turn of the century and continued until nearly 10 years ago. As much as 30,000 cubic yards of sand were removed annually, according to O'Brien. Such removal would impoverish the beach in a downdrift direction, and it is possible that the relatively recent erosion between Miramar and Princeton may have arisen from this interference with normal beach drift. The erosional aspects are discussed later, but if the reasoning applies, it indicates predominant northward shore currents in the bay.

Despite the lack of direct observational evidence, the writer agrees with O'Brien's conclusion of 1930 that the net shore drift is from Point Miramontes toward Pillar Point.

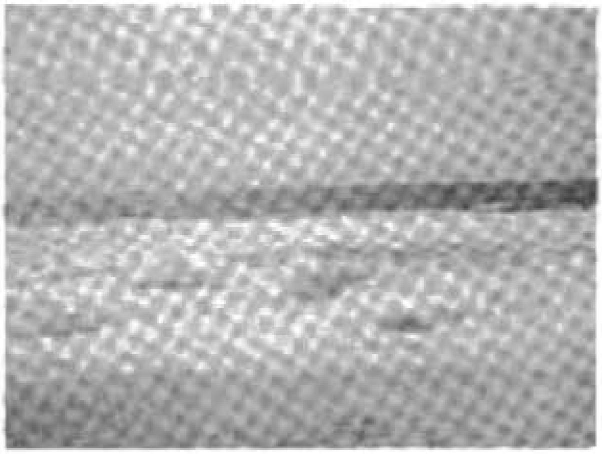
g. Wave Refraction and Wave Energy in Halfmoon Bay. - Differences in wave height along the bayshore are evidence that refraction controls the distribution of wave energy along the shore. The refraction pattern is a function of the boundary conditions within the bay, of the direction of wave approach, and of the wave period. A refraction diagram was prepared, using the principles described by O'Brien and Mason in their summary of wave theory. Figure 2 was used as a base map. Waves of 12-second period were brought in from northwest, to reproduce approximately the conditions on April 25.

Figure 17 shows the refraction pattern. It was assumed for simplicity that refraction does not occur until depths of 100 feet or less are encountered. The projected distances of travel of the wave were taken as the product of the average velocity between the limiting depths and the time of advance (chosen as 36 seconds for convenience). The effect of the southeast reef is probably greater than that shown on the diagram, because the graphical results are in part a function of the time interval chosen. That cross-waves are generated by the reef is supported by observation, however. On may 9 waves of essentially the same period were approaching the shore from two directions at station 5. The shore current inside the plunge line was to the south, suggesting a stronger effect of the southward refracted waves. The interference pattern may also bear on the observations of a local fisherman that drift tends to accumulate in this vicinity.

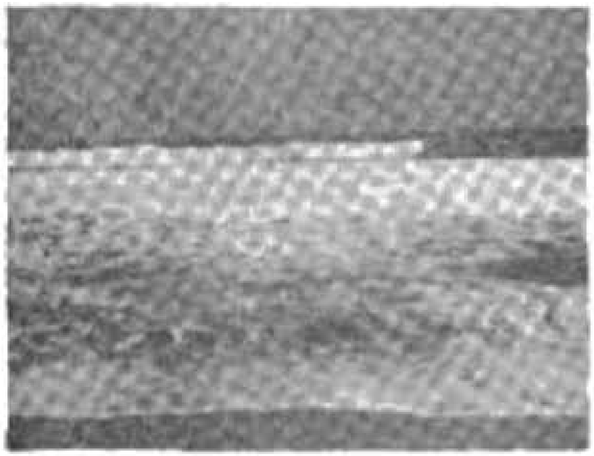
The principle that adjacent orthogonals to the wave crests inclose regions across which no power flows laterally was used to appraise the energy distributed along the beach. The distances between the orthogonals along the beach in figure 17 were measured, and from their reciprocals the proportional power was computed. The relative wave energy along the beach was also computed from the wave observations on the principle that the energy of any wave is proportional to the square of its amplitude. The results of the computations are given in table 9 and are shown in figure 18.



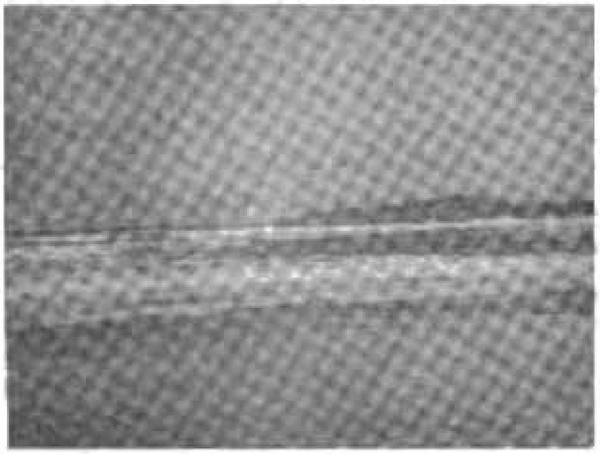
Breaking waves at Station 2, 2 p.m., May 2, 1942.



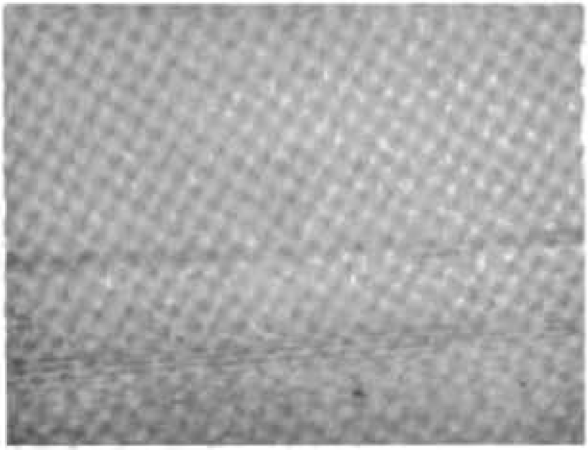
Breaking waves at Station 3, 3 p.m., May 2, 1942



Breaking waves at Station 5, 12:50 p.m., May 2, 1942.



Breaking waves at Station 11, 11 a.m., May 2, 1942.



Breaking waves at Station 13, 10:40 a.m., May 2, 1942.

PLATE II

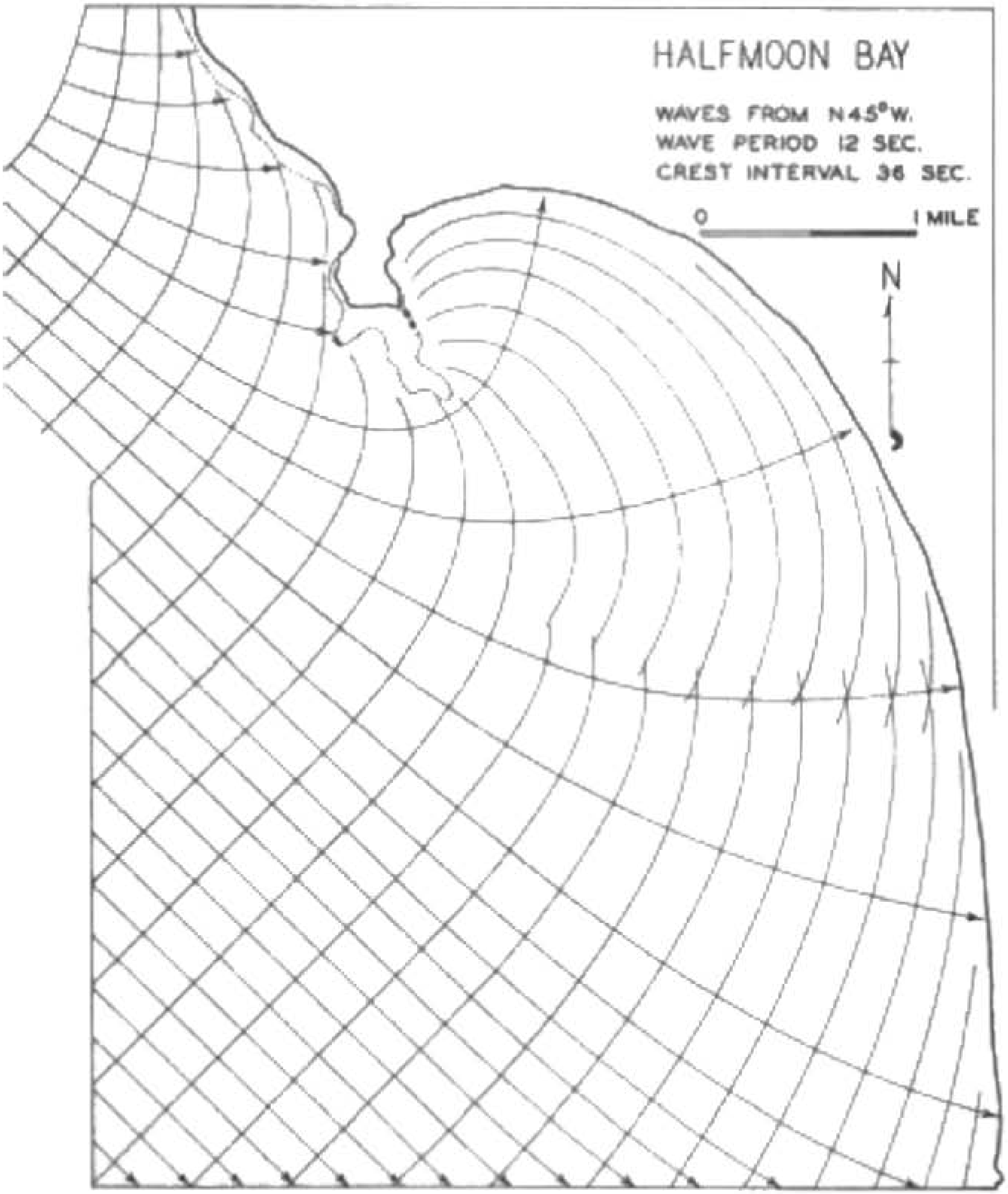

HALFMOON BAY
WAVES FROM N45°W.
WAVE PERIOD 12 SEC.
CREST INTERVAL 36 SEC.
0
1 MILE
N

Table 9

Relative Wave Energy, $(h/h_o)^2$

(Here h_o is the greatest h recorded on the given date. Cf. Table 8.)

Station	4/18/42	4/25/42	5/2/42	5/9/42
1				1.00
2	1.00	1.00	0.92	
3	0.98	0.92	1.00	1.00
4	1.00	0.68		
5	0.86	0.82	0.92	0.96
7	0.73	0.70		
8			0.51	0.55
9	0.55	0.39		
10	0.41	0.33	0.38	
11		0.23		
12	0.23		0.21	0.20
13	0.134			0.09

Boat Data

Station	4/26/42
6	0.80
8.6*	0.50
11.7	0.156
13	0.011

Refraction Diagram Data

Station	4/25/42
2	1.00
3.5	0.86
6.6	0.71
10	0.48

* Station 8.6 lies 0.6 of the distance between 8 and 9.

The curved line in figure 18 shows the trend of relative energy per unit crest length per unit time on the basis of the shore observations. The refraction diagram gives results in good agreement with this trend, although the slope of the line joining these points is less steep than that for the wave observations. Nevertheless, the diagram indicates at least the order of energy decrease along the shore, and in the absence of other data would be acceptable as a first approximation.

RELATIONS BETWEEN WAVE ENERGY, BEACH SLOPE, AND SAND SIZE

In the first section of this report it was pointed out that a complete beach study includes information on the boundary conditions, the beach materials, and the energy of the system. It is appropriate to consider how the relative energy along the shore corresponds with the other observed data.

Figure 19 shows a linear relation between beach slope and relative wave energy at all stations where the two were measured at the same time. The equation of the straight line is

$$S = kE + K \quad . \; . \; . \; . \; (5)$$

where E is the relative energy. The constant k has the value 10.0, and K has the value 0.6.

The widest scatter of the points occurs where the slope is most steep. These points also fell below the predicted straight line of equation 4 in figure 14. Thus the boundary conditions, represented by rock reefs, do exert an influence on the beach slope, although the general agreement of the trends in figures 5 and 18 indicates that the energy relation is probably the more important of the two.

The relations expressed in the equations previously given permit further predictions, first of the relation between relative energy and sand size, and second between relative energy and distance along the shore. Inasmuch as beach slope and energy are linear, and beach slope and sand size are logarithmic (equation 3), one may predict that sand size is a positive exponential function of relative energy. This may be shown by eliminating S from equations 3 and 5 and solving for r:

$$(1/b)\log_e(r/R_o) = kE + K$$

$$r = R_o e^{bK} \, e^{bkE} \quad . \; . \; . \; . \; . \; . \; (6)$$

Equation 6 indicates that if r is plotted against E on semi-log paper, a straight line should be obtained, in which the parameters may be determined from previous knowledge. Thus from table 7 we have $b = 0.23$ and $R_o = 0.07$. From figure 19, $k = 10.0$ and $K = 0.6$. Hence $R_o e^{bK} = 0.08$, and $bk = 2.3$, so that the predicated line is

$$r = 0.08 \, e^{2.3E}$$

The straight line of figure 20 is drawn according to the prediction, and indicates a satisfactory agreement.

In similar manner the functional relationship between relative energy and distance along the shore may be found by eliminating S between equations 4 and 5 and solving for E:

$$kE + K = -(a/b)x + (1/b)\log_e(r_{\alpha}/R_o)$$

$$E = -(a/bk)x + (1/bk)\log_e(r_{\alpha}/R_o) - (K/k) \quad . \; . \; (7)$$

Again the parameters of the line may be predicted. The slope of the line is $-(a/bk) = -0.178$, and the y-intercept is $1.252 - 0.06 = 1.192$. Figure 21, redrawn from figure 18, shows the predicted line. The slope has been drawn in accordance with the different scale units. The values above 1.0 on the energy axis are imaginary, and indicate that the linear relation begins at the point along the beach where refraction due to Pillar Point and the southeast reef begin to manifest themselves.

The internal consistency of the observational data from Halfmoon Bay strengthens the writer's belief that if relatively simple natural situations are chosen, it is possible to discern the underlying physical laws which control the behavior of matter in the environment. A purely theoretical approach, with a prediction of the exact nature of all the functions, is probably not possible at the present state of knowledge, but a combined observational and analytical attack is feasible. From a theoretical viewpoint, equations 5 and 6 are probably the most fundamental of those given, because they bring in the relations of sand size and beach slope to the relative wave energy. The rates of change of these two equations are:

$$dS/dE = k$$

$$dr/dE = bkr$$

From these relations it would appear that the slope is a linear function of energy essentially independent of other factors, whereas average sand size is influenced by itself and by the slope relations along the beach. Before the full implications of these equations can be analyzed, additional beaches of the same general type as Halfmoon Bay should be investigated.

EROSION AND DEPOSITION AT HALFMOON BAY

Comparison of earlier maps with the latest chart of Halfmoon Bay shows no noticeable change in the general alignment of the shore. This suggests a stable strand, but field evidence throws some doubt on the subject. A stable beach would have a source of material to replenish the annual down-beach drift of sand, so that a steady state shoreline would occur along the entire stretch. At the down-beach end of the bay would be a trap or other means for disposing of the transported material, such as a belt of sand dunes. Along Halfmoon Bay erosion is active near Point Miramontes, but it is also active near Princeton. Moreover, there are no dunes near Pillar Point, and the dunes which do occur are near the center of the bay shore. The situation along the bay is therefore not simple, and the following sections attempt to explain the observed conditions.

a. <u>Estimates of the Rate of Erosion</u>. - At the base of the cliff near Point Miramontes and for a mile north occur several semi-conical masses of freshly slumped terrace material, which are subject to active wave attack. An estimate of the volume of one of these masses yields the value 70,000 cubic feet, so that some 200,000 cubic feet of sand and gravel had recently slumped from the terraces. (See Plate III.) The material is relatively unconsolidated and probably slumps readily as a result of undercutting. If only 10 such slides occur per year over the mile stretch, approximately 700,000 cubic feet of material is washed away annually. This is equivalent to about 26,000 cubic yards. It is perhaps a coincidence that this figure is nearly the same as O'Brien's estimate of annual sand transport based on operations of the sand pit at Pilarcitos Creek.

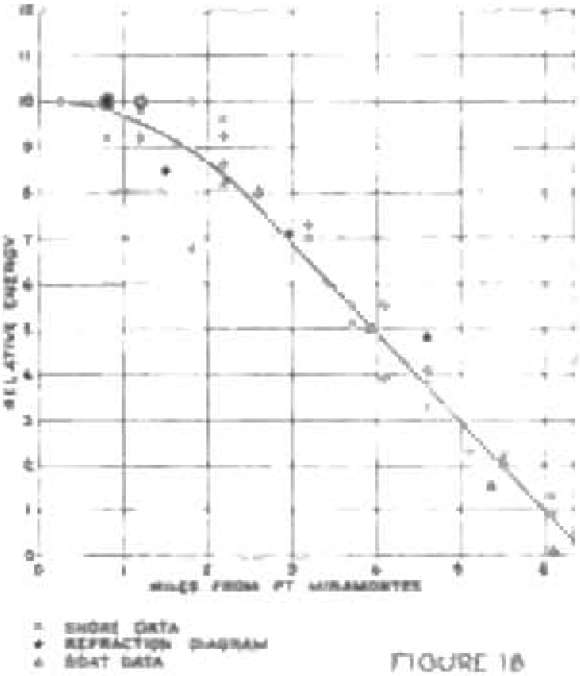


FIGURE 18

OBSERVED RELATION BETWEEN RELATIVE WAVE ENERGY AND DISTANCE

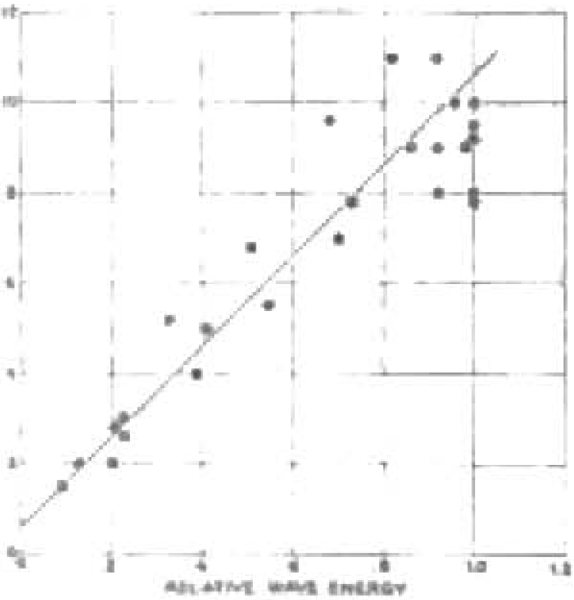


FIGURE 19

OBSERVED RELATION BETWEEN FORESHORE SLOPE AND RELATIVE WAVE ENERGY

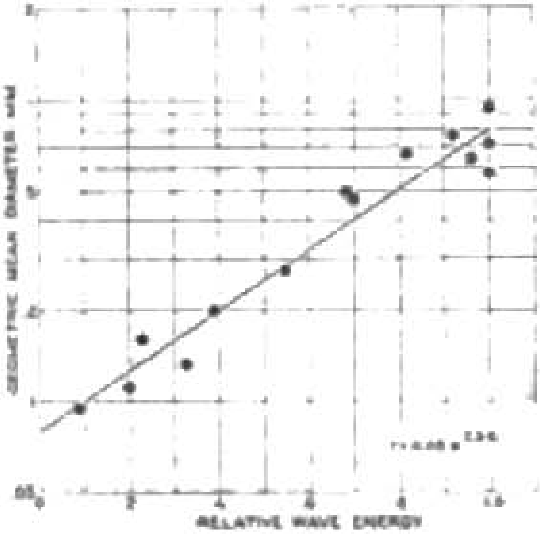


FIGURE 20

PREDICTED RELATION BETWEEN SAND SIZE (r) AND ENERGY (E)

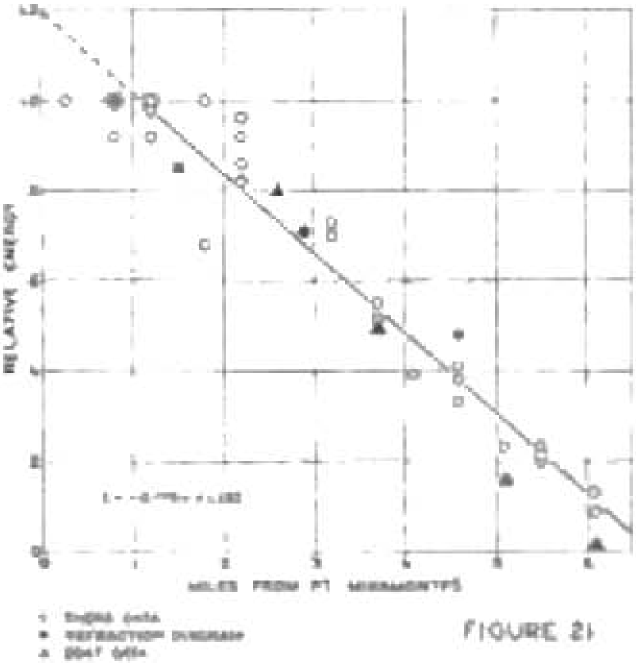


FIGURE 21

PREDICTED RELATION BETWEEN RELATIVE WAVE ENERGY (E) AND DISTANCE (X)

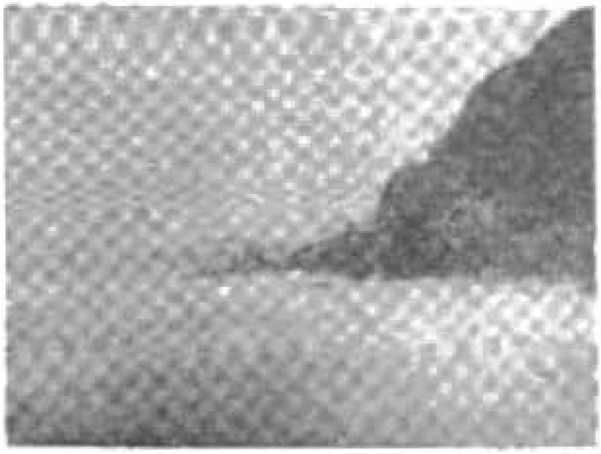
A local resident informed the writer that about 25 years ago a road ran along the edge of the terrace south of Princeton. He estimated that its eastern margin was perhaps 40 feet from the edge of the cliff. Since that time erosion has cut away all but small patches of the pavement. The cliff is about 20 feet high, and the eroded stretch is approximately a mile long. Hence the volume removed is equivalent to about 4 million cubic feet of terrace material. Allowing 25 years for the process, the annual removal becomes 6,000 cubic yards. Add this to the 26,000 cubic yards from the southern cliffs, and the total annual removal per year along the bay shore is of the order of 32,000 cubic yards.

b. Estimates of the Rate of Accretion. - If some 30,000 cubic yards of terrace material is annually fed to the beach, there should be evidence of its accumulation somewhere within the closed system, or a mechanism for removing it from the system. Two possibilities are open, (1) the beach material is abraded to fine mud during its movement and is carried out to deep water beyond the bay; (2) the material accumulates partly in the sand dunes along the shore, and partly over the bay bottom.

Recent studies have largely supported the view that abrasion is essentially a second-order term in accounting for size decrease along beaches or in streams. A recent report by the Beach Erosion Board establishes fairly conclusively that abrasion on sand beaches is essentially negligible, a conclusion with which the writer concurs. A study of the sphericity, roundness, and mineral content of the sand samples will shed some light on this question, but from the writer's experience it is most likely to support the present view.

Selective transportation is a much more important process than abrasion in the segregation and removal of material. Selection may be affected by wind or by waves and currents. Sand dunes in general may be considered as traps for beach sand. They occur where deposition exceeds transportation, or where favorably directed winds remove sand from the beach. Along Halfmoon Bay dunes occur most prominently between stations 7 and 8, and less so between stations 5 and 6. The dune belts are very narrow and relatively low. The edge of the terrace projects through the dunes locally, indicating that they are mainly a veneer of sand blown up on the terrace. The photographs of Plate IV illustrate these conditions. If one estimates the dune volume liberally, by assuming them to be 1 mile long, 100 feet wide, and 15 feet high, he arrives at the value 7.5 million cubic feet, which is equivalent to about 280,000 cubic yards. This is less than 10 times the annual sand movement along the beach. Considering that the bay has been present for several thousand years at least, this figure becomes negligible. Hence even under a selective transport assumption, the most reasonable explanation is that the material is carried out into the bay or beyond.

The area of the bay bottom is approximately 5.5 square miles within the zone inclosed between the curve of the bay shore and a straight line from Pillar Point to Point Miramontes. This is equivalent to approximately 17 million square yards. Hence it would require more than 180 years for the annual beach increment to form a layer 1 foot deep over the bay bottom. The corresponding average annual deposition of about 0.006 foot would not be detectable over the time that reliable surveys are available. Even considering that the material would not be uniformly distributed over the bottom, a slight shoaling of water here, and the filling of a



Erosion at Station 2, April 18, 1942.

Erosion just south of Station 2, May 2, 1942

Segment of old road at Station 11, May 2, 1942.

Eroded terrain behind sea wall at Station 12, May 2, 1942.

PLATE III

depression there, would hardly be detected.

c. Topographic Analysis of the Sand Dunes. - The topography of the dunes between stations 7 and 8 is hillocky, and the configuration of the surface suggests predominant sand movement to the southeast. This suggests that most of the sand is picked up near station 8 and blown upbeach diagonally to station 7, rather than being blown inland normal to the beach at both stations. This was tested by taking sand samples from the dune crest at the two stations. The results show that the sand is finer to the south, in contrast to the beach sand, which is finer to the north. Table 10 gives the size data.

Table 10

Comparison of Dune and Beach Sand at Stations 7 and 8

Station	Beach Sand		Dune Sand	
	Geom. Mean		Geom. Mean	
7	0.40 mm.	0.80	0.19 mm.	0.37
8	0.33	1.60	0.21	0.37

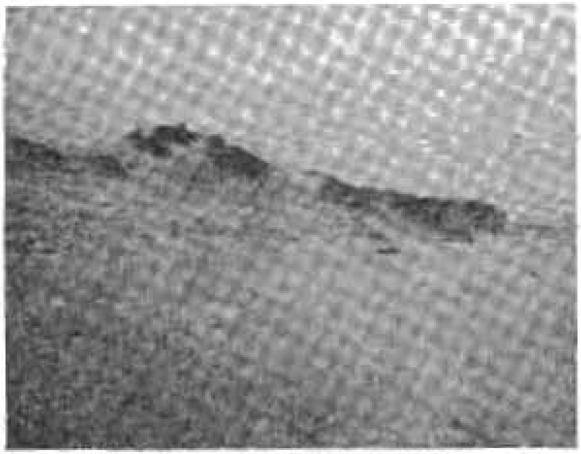
Although two samples are not sufficient to demonstrate the direction of transport, they do support the topographic analysis of the dunes.

The location of the principal dunes near station 7 rathen than near station 13 is probably a function of sand size and of prevailing winds. The fine sand at station 13 remains wet indefinitely, whereas that at station 7 dries rapidly on a relatively high berm. The trough east of Pillar Point may also influence the northwesterly winds so that they are directed against the beach in the vicinity of station 7. In terms of the introductory remarks in this report, a complete energy analysis of the system should include measured data on the winds. This aspect was not included in this study.

CONCLUDING REMARKS

The present report includes mainly the field observations made during the study. Much more detailed information is available on the geology of the terraces, but this material is deferred until the shape, roundness, and mineral composition of the beach samples are studied.

The writer believes that this report in its present form offers a strong argument in favor of detailed scientific studies of selected beaches as a supplement to the engineering studies now made. The principles developed during such studies will undoubtedly find an immediate application to problems of beach stabilization and control. The role of energy in the system deserves much more study, and reliable and convenient methods should be developed to obtain data on wave heights and periods, both in the open sea and near shore. Methods of estimating currents should also be improved.

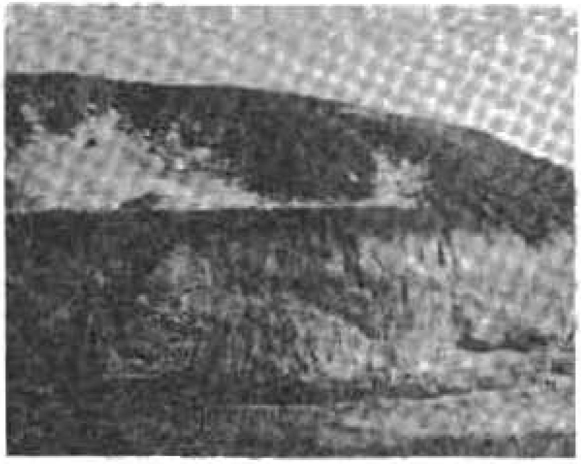


Main dune ridge south of Station 7. April 18, 1942.

Crest of dune at Station 8, looking southeast. May 2, 1942.

Dune fringe at Station 5, looking north. May 2, 1942.

Terrace material outcropping through dunes, Station 8. May 2, 1942.



Relation of dunes to terrace shown in stream cut north of Station 7. May 2, 1942.

PLATE IV

The writer is indebted to Professor M. P. O'Brien for many helpful suggestions regarding this study. He is also indebted to Dr. C. M. Gilbert of the Department of Geology at Berkeley for his assistance in the field work. Dr. M. A. Mason, Principal Engineer of the Beach Erosion Board, made helpful suggestions in the manuscript.