CHAPTER 23

NEARSHORE SEDIMENT MOVEMENT - CENTRAL CALIFORNIA COAST

J. W. Johnson
Professor of Hydraulic Engineering
University of California
Berkeley

ABSTRACT

An 80-mile reach of the central California coast, extending from the mouth of the Russian River in the north to Half Moon Bay in the south, was studied for the characteristics of sediment movement in the nearshore zone. From the results of a large number of beach and offshore sediment samples and other information, several techniques were utilized in appraising the nature of sediment movement along the reach of the coastline under study. These techniques included: (a) the physical nature of the coastline from a consideration of the prevailing wave energy, (b) the distribution of light and heavy minerals and their sources, (c) the use of certain naturally radioactive minerals and their use as a tracer, and (d) the sedimentation experience at harbors where both natural and stabilized entrances exist.

INTRODUCTION

Along any reach of coastline where navigation works and other coastal structures exist or are contemplated, patterns of net or long-term littoral and offshore sand movement are vital information for the proper engineering design and maintenance of such improvements. A reach of coastline containing numerous navigation works, or where new works might be constructed in the future, is that which extends from the mouth of the Russian River to Half Moon Bay (Fig. 1). In this reach existing harbors are now located at Bodega and Half Moon Bays, maintenance dredging is necessary in the main ship channel across the San Francisco Bar, and new works conceivably could be constructed at Tomales Bay, Drakes Estero, and Bolinas Lagoon. Over the past few years numerous studies on this 80-mile reach of coastline have been made by the University of California on various aspects of nearshore sediment movement. A brief summary of these various studies along with an interpretation as to the general nature of nearshore sediment movement in the area is presented. Basically the information consists of a geological summary (12)*, data on beach profiles at various locations and times (20-23, inclusive), sand transport by wind (9, 27), tracing littoral movement by naturally radioactive minerals (10, 19), and the analyses of heavy minerals of beach and bottom samples (5, 13, 18).

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*See References

GEOLOGICAL CONSIDERATIONS

The Pacific Coast of the United States has been subject to both uplift and depression over geological time (4). The present-day physical characteristics of the reach of shoreline between the Russian River and Half Moon Bay (Fig. 1) consists of several prominent headlands, extensive stretches of sandy beaches, and many miles of intermittently rocky and beached shore (5, 12). Only the Russian River and the discharge through the Golden Gate are significant as supplies of stream-borne sediments to the coast. The most prominent headlands are Bodega Head, Point Reyes, Duxbury Point, Pedro Point, and Pillar Point. Some of these are composed of a granitic diorite which has considerable significance in the discussion below with respect to heavy mineral analyses.

Evidence exists to indicate that various stands of sea level existed in the past along this reach of coastline. Perhaps the lowest stand was a pronounced lowering of relative sea level (on the order of 200 ft.) which probably was related to the last large glacial lowering of sea level (12). Such a lowering of relative sea level could have resulted in the moving of the littoral zone out away from the obstructing influence of the present-day headlands and into a zone that might have been conducive to large-scale downcoast transfer of sediment. The low stand of sea level and renewed stream activity probably accounts for the deep rock trenches in the Russian River channel and in the Golden Gate.

Following this period of a low stand, a rise in relative sea level took place and brought sea level to its present stand. This rise in sea level simultaneously decreased the amount of sand contributed by certain formations (the Franciscan) by limiting stream erosion, increasing the addition of dioritic material, and by extending cliff erosion. In areas which are backed by relatively softer strata, cliff erosion during this present period apparently has not been great because the sea has not advanced very far beyond the zone previously eroded during early periods.

The present configuration of the shoreline is typical of conditions observed throughout the world where wave energy predominates from one general direction--in this case from a northwesterly direction. Thus, from an idealized standpoint the shoreline planform of the various embayments shown in Figure 1 can be represented as shown in Figure 2. Over geological time the waves refracting around the resistant headlands have scoured away the less resistant or erodible material in the lee of the headlands. As long as the wave fronts break at an angle to the shore, a littoral current will occur. Erosion of the shoreline will continue until the planform of the shoreline is so shaped that little or no littoral current will exist; consequently, the shoreline will be in a relatively stable condition. During storms when waves may arrive from other than the predominant direction,

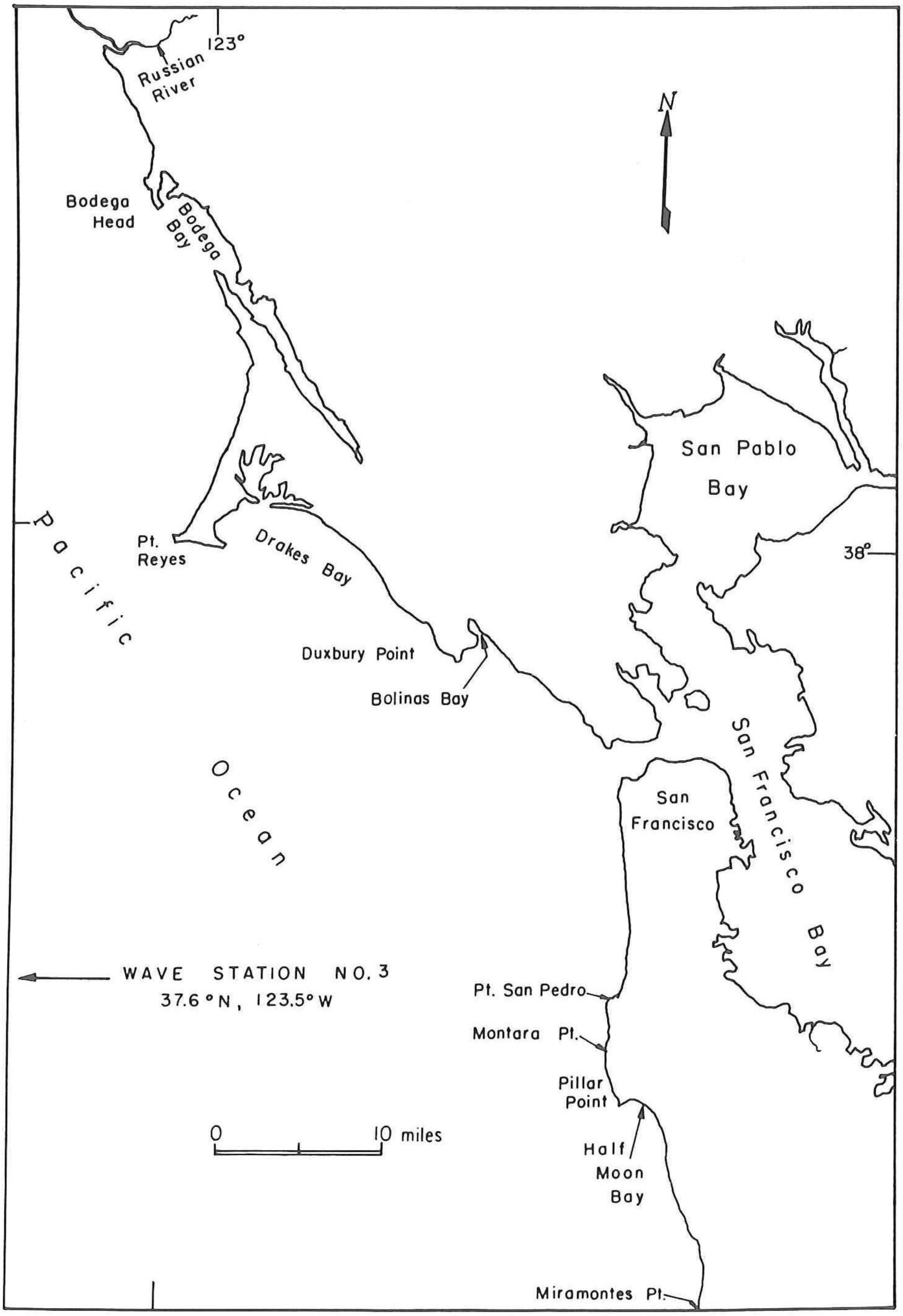


Figure 1. Vicinity map - central California coast

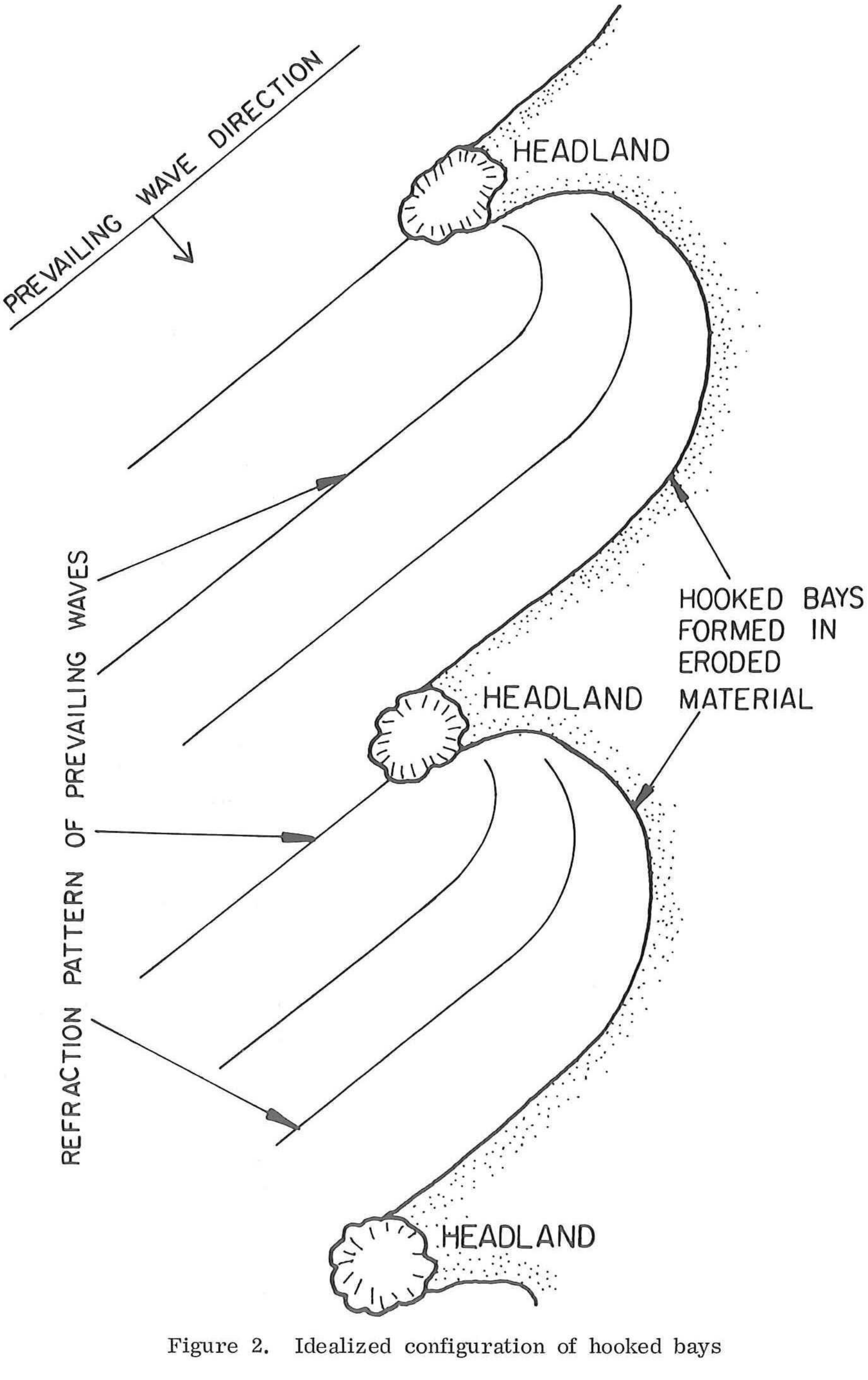


Figure 2. Idealized configuration of hooked bays

a littoral current will exist and littoral transport will take place for the duration of the storm. Although the reach of shoreline between the Russian River and Half Moon Bay appears to be in stable equilibrium with respect to wave action with very little net littoral transport, other evidence as discussed below is necessary to confirm such a conclusion.

WAVE CLIMATE

Since wave energy is the principal factor in moving nearshore sediments, a knowledge of the predominant wave direction is the most reliable method of establishing the prevailing direction of littoral drift. Whether or not an appreciable littoral drift will occur depends, of course, on the available supply of sediment (8). That is, little or no littoral drift along a coast will occur if no appreciable supply of sand occurs to the coast even though wave energy is available to transport material.

A typical example of the presentation of the wave climate at a given locality is shown in Figure 3. These data on the frequency of occurrence of waves of various heights from various directions were assembled as "wave roses" for both sea and swell (14). These data are for a deep-water station offshore of San Francisco, California (see Figure 1 for location) which was one of seven stations along the 1000 mile California coastline for which such information was compiled by the hindcast procedure. In addition to the summary of prevailing wave conditions as illustrated in Figure 3, data were also compiled for three northern California stations on wave statistics for the ten most severe storms that occurred during a selected ten-year period (15). These latter data are useful for arriving at an estimate of the maximum wave condition for the structural design of coastal works.

It is evident from an examination of Figure 3 that the predominant wave direction is from a northwesterly direction; consequently, for the reach of California coast shown in Figure 1 a general drift of sediment in a southerly direction is to be expected. In a following section on the rate of littoral drift it will be seen that the annual rate of drift along this section of the coast is relatively small--primarily because of an apparently relatively small supply of sand to the coast.

CHARACTERISTICS OF BEACH AND NEARSHORE SEDIMENTS

To provide further information on littoral processes, several hundred samples from the beach and offshore zones were collected (5, 13, 18) and then analyzed petrographically for heavy mineral content and mechanically for grain size distribution. A brief summary of the general results of the various aspects of these analyses is as follows.

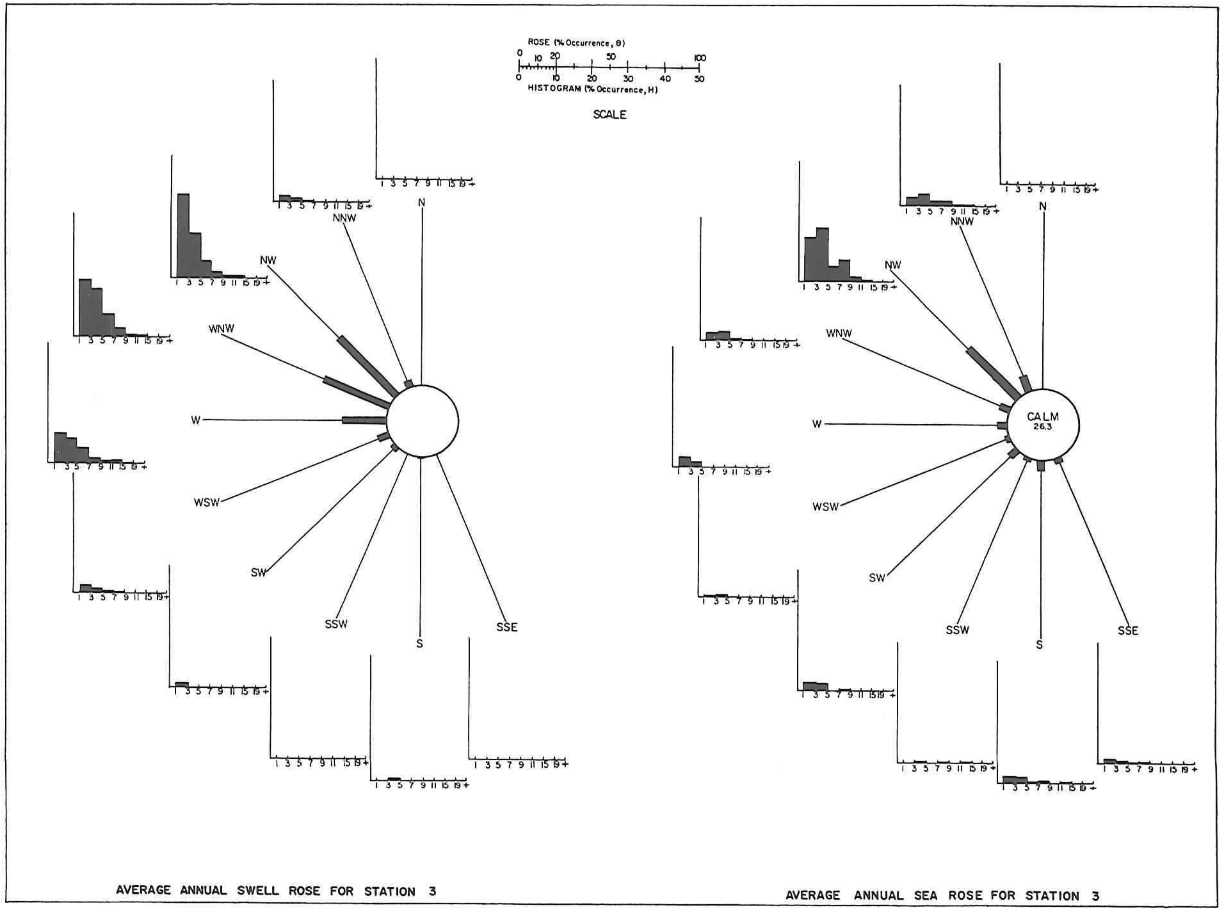


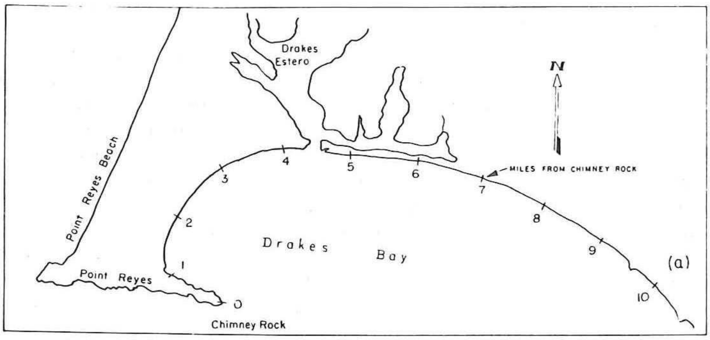
Figure 3. Sea and swell roses for a station off the California coast at 37.6° N, 123.5° W (see Ref. 14)

(a) Mechanical composition of beach sand. A comparison of the median diameters of a series of samples taken in a consistent manner along a coast frequently shows progressive variations. A decrease in the grain size with distance from the source generally is interpreted as also being the prevailing direction of drift. Such a procedure requires careful sampling and caution in drawing conclusions in order not to confuse variations in grain size which result from refraction effects with those due to transport along the coast. For example, for Drakes Bay, California, Figure 4b shows the variation of mean grain size at the mid-tide level along the shoreline of the bay (Figure 4a). The observed decrease in grain size with distance westward along the beach from the entrance of Drakes Estero is a result of wave exposure due to refraction of the prevailing northwest swell into the bay and not a decrease in grain size from a source located to the east and south. Prevailing wave conditions (Figure 3) and a consideration of the orientation of Drakes Bay (which is typical hooked bay as discussed above) definitely indicates a tendency of a southerly littoral drift. Whether or not this drift is appreciable is discussed elsewhere.

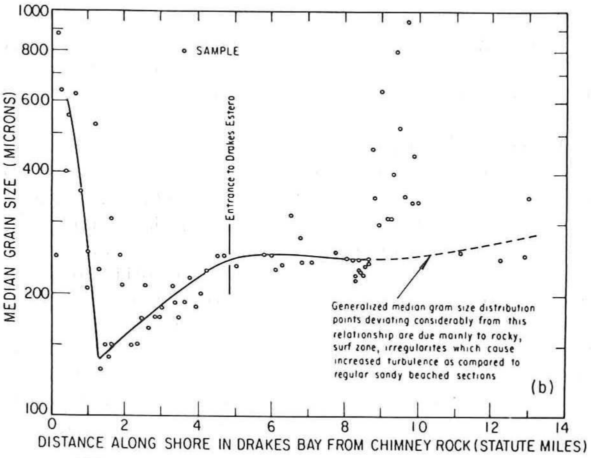
(b) Heavy mineral studies. From the petrographic analyses of the various nearshore sediments petrologic provinces were outlined. These provinces were distinguished on the basis of gross differences in the heavy mineral composition of the sands occurring along the coast. The constituent minerals generally fall into three main categories: (1) the "dioritic" minerals which are derived from the diorite bodies at Bodega Head, Tomales Point, Point Reyes, Montara Point, and Pedro Point (Figure 1), (2) the so-called "non-dioritic" minerals which are derived principally from the Franciscan or sources related to the Franciscan, and (3) other minerals which are considered as essentially non-diagnostic (the association of high concentrations of carbonate and high percentages of zircon relative to the other Franciscan-derived minerals).

An example of the distribution of minerals is shown in Figure 5 where the ratios D/N (percent of dioritic minerals to percent of non-dioritic minerals) are indicated for the various provinces. The high values of these ratios in close proximity to each headland composed of dioritic materials indicated very little transport of minerals away from their source. The distribution of minerals along the entire coast under discussion is shown in Figure 6 but with a slightly different method of representation being used to summarize the data from the various investigators (5, 13, 18).

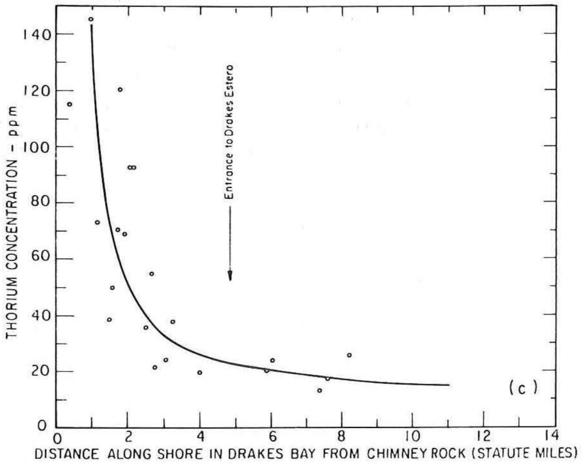
There are several possible explanations as to why these various distinct mineralogic assemblages come to occur in their present locations and from where they were derived (12). One explanation assumes that sand continually moves downcoast from the mouth of the Russian River (the only stream of consequence) (Figure 1). If such is the case, zones of discrete mineralogic assemblages could persist only if the supply of sand from each succeeding main downcoast source of local sands (sands bearing a distinctive local mineralogic composition) are sufficiently large so as to cause (a) 'flooding out' and masking of mineral assemblage carried along by the sands moving in from adjacent areas upcoast or (b) mixing and diluting of the incoming sands sufficiently to produce a new assemblage of minerals which would be characteristic of neither the incoming sands nor the local source of sediment.



DRAKES BAY, CALIFORNIA



MEDIAN GRAIN SIZE vs DISTANCE ALONG THE SHORELINE AT DRAKES BAY



THORIUM CONCENTRATION vs DISTANCE ALONG THE SHORELINE AT DRAKES BAY

Figure 4. Distribution of sand size and thorium concentration along Drakes Bay shoreline

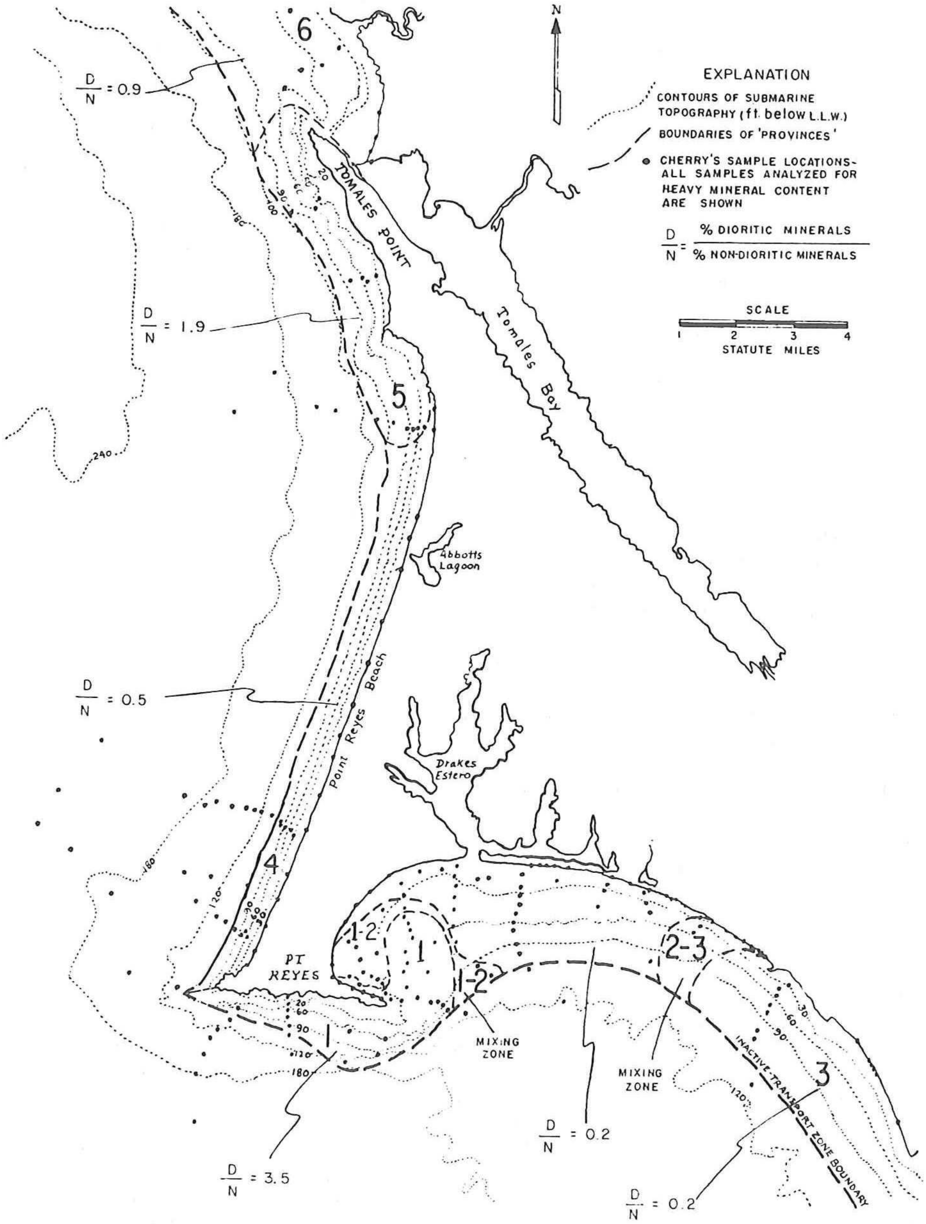


Figure 5. Heavy mineral distribution in the Tomales Point - Drakes Bay area (see Refs. 5 and 12)

A second explanation is that the mineralogic provinces exist because there is little or no downcoast transport of sand at the present from the Russian River or other sources. The provinces would therefore merely reflect the fact that, for the sands in each province, there would be essentially only one source -- local detritus supplied from streams and cliff erosion.

A third explanation is that certain of the provinces reflect transport and deposition which took place before the present cycle of erosion and sedimentation while other provinces reflect the effects of recent local deposition. Such an explanation would imply that in certain areas little or no sand is coming from either present-day local sources or downcoast transport, or at least the supply of sand from either of these present sources is not sufficiently large to cause the effective masking or diluting of the older deposits occurring in particular localities.

Regardless of which of the three explanations most closely represents true conditions, each one involves processes which effectively eliminate the possibility of continuous movement of large amounts of sand along this part of the coast, particularly the movement of sand derived from a single primary source such as the Russian River. In general, therefore, it appears from the heavy mineral studies that the littoral transport of sediment along the reach of coastline under consideration is only of local importance. Also, the sand-sized sediments in more than 90 to 120 ft. of water tend to lack physical connection to mineralogically similar sediments on the modern coast, and therefore must be products of an earlier period of sedimentation. Of additional interest is that the San Francisco Bar has essentially the same mineralogy as the sand channel in the Bay west of Carquinez Straits and must be derived from this channel.

(c) Tracers. The movement of nearshore materials often can be traced by means of either natural or artificial "tagging" of the sands. The use of natural tracers can be used to advantage only on a coastline where certain distinctive minerals are fed into the littoral zone at certain discrete localities. For example, along the central California coast various headlands composed of granite diorite slowly feed certain naturally radioactive minerals into the nearshore area as a result of wave erosion (10). Sampling of these nearshore materials, heavy mineral separation, and analysis in a gamma-ray spectrometer (10, 19) provides information on the variation in concentration of the radioactive minerals with distance from the source and, consequently, the prevailing direction of drift. For example, in Figure 4 the concentration of thorium at various locations along the shoreline of Drakes Bay is shown. It is evident from an examination of this plot that a source of naturally radioactive material apparently occurs at Point Reyes. Over geologic time such minerals have slowly been moved east and southward along the shoreline of Drakes Bay, thus indicating a slow but prevailing southerly drift.

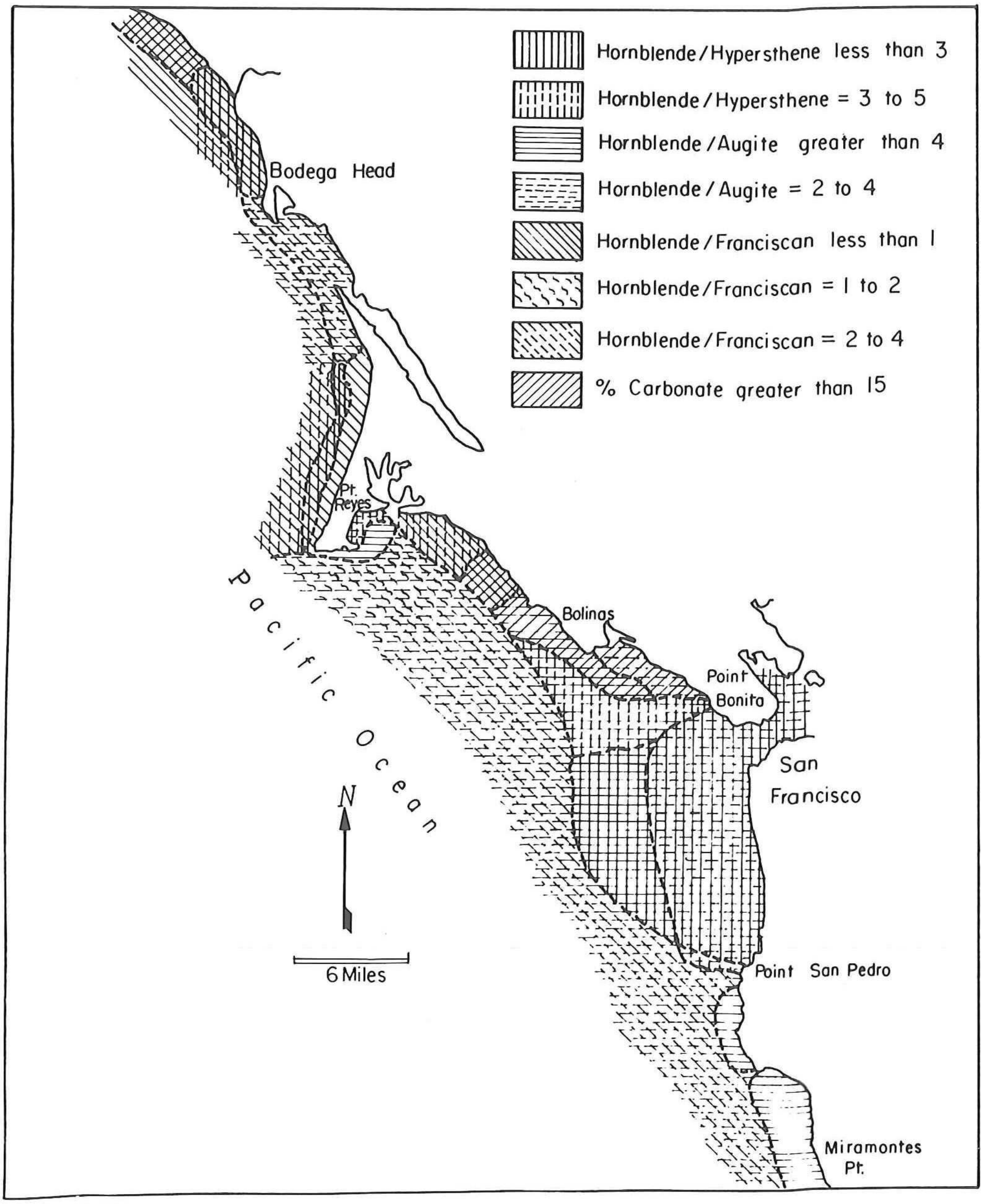


Figure 6. Offshore Distribution of surface sediments from the Russian River to Miramontes Point, California

Figure 7. Aerial view looking southeast at Bodega Bay (Salmon Creek Beach in the foreground; Tomales Bay, Tomales Point and Point Reyes in the background)

As to artificial tracers, considerable research over the past few years has been devoted to tagging sediment by radioactive and color processes. Such methods have been used for materials in both the sand and the clay sizes (6). A discussion of the procedures used in the numerous part investigations is beyond the scope of this paper, and the reader is referred to recent articles in various technical journals for an appraisal of the present state of the art (3, 6, 7, 17). It is of importance to note that for the correct establishment of the prevailing direction of drift the use of artificial tracers requires frequent introduction, sampling, and analysis of the tagged sediments throughout the year. Needless to say, such investigations are expensive, may involve a health hazard, and may be inconclusive. If other procedures for establishing direction of drift can be utilized at all, they probably would in most instances be more preferable than the use of artificial tracers.

SEDIMENTATION AND NAVIGATION WORKS

As illustrated by Figure 2 hooked-bays are typical features of a coastline subjected to waves from a predominant direction. Such a feature is a definite indicator of the prevailing direction of littoral drift but gives no information on the rate of drift. As discussed above, a hooked-bay has a configuration indicating a tendency toward equilibrium in which little or no littoral drift occurs. Whether or not complete equilibrium has been established, however, is often difficult to determine.

The hooked-bays in the reach of coastline under study are Bodega Bay, Drakes Bay, Bolinas Bay, and the Half Moon Bay (Figure 1). Drawings of these four bays are shown in Figures 8 to 11, inclusive. The first three of these bays are connected to a lagoon behind the barrier beach by a tidal entrance. The principal features of each bay are discussed briefly as follows.

Bodega Bay. This hooked-bay has been formed by erosion due to wave action on the relatively soft material in the lee of the more resistant dioritic material which forms Bodega Head. North of Bodega Head the slow southward littoral drift has accumulated to form Salmon Creek Beach (Figure 7). This beach is an equilibrium shoreline which is conducive to the formation of sand dunes (27); that is, the basic conditions for the existence of a dune area are; (a) a supply of littoral drift, (b) a shoreline orientation approximately parallel to the crests of the prevailing wave condition, thus creating a favorable condition for a low littoral drift, and consequently a location for sediment accumulation, and (c) low topography back from the beach where prevailing northwest winds can easily move the sand inland from the area of accumulation. This dune area behind Salmon Creek Beach is clearly evident in Figure 7. Calculations show the annual loss of sand from Salmon Creek Beach to be approximately 11,000 cu. yds. per year (9). Much of this material appears to be blown into Bodega Harbor. The original tidal entrance to the lagoon was located as shown in Figure 8. This entrance is at the extreme western end of the Doran Beach sandspit in the immediate lee of Bodega Head where refraction effects give wave heights which can be expected to be less than any other location along the shoreline of Bodega Bay (2). The entrance was stabilized by jetties in 1943 (Figure 8). Experience has shown that no maintenance dredging due to littoral drift has been necessary since construction of the jetties. Apparently, therefore, most of the littoral drift to the north of Bodega Head comes to rest at Salmon Creek Beach and is blown inland to form sand dunes. This confirms the heavy-mineral analysis discussed above which indicates that very little sand movement apparently is occurring in the nearshore zone in the locality of Bodega Head.

Drakes Bay. Except for being much larger in size, Drakes Bay is similar to Bodega Bay and vicinity; that is, there are sand dunes to the northward of the Point Reyes dioritic headland, a hook-bay open to the south with a lagoon (Drakes Estero) connected to the bay by a tidal entrance. As in Bodega Bay the tidal entrance to the lagoon tends to be located at the most westerly part of the lagoon where refraction effects cause heights of the prevailing waves to be less than at any other point along Limantour Spit. High ground immediately west of the entrance of Drakes Estero (Figure 9) prevents the inlet from being moved closer to Point Reyes where, due to refraction, the wave heights are appreciably lower than elsewhere along the spit. Actually, over the last 100 years the entrance to the lagoon has shifted positions at random over a distance of almost a mile. The location at any one time appears to be somewhat due to chance, in which the heavy wave action existing during storms from the south, accompanied by extreme high tides, may breech Limantour Spit at a low point. Such a breech then may be enlarged by tidal currents during subsequent tidal cycles, and the old entrance closed by wave action. The entrance may remain in such a position for years before a combination of high waves, tidal currents and high tides cause the entrance to either slowly migrate or suddenly shift to an entirely new position.

No information is available on sand movement at the entrance of Drakes Estero. Little movement would be expected from the highly refracted waves from the northwest, but in storms which generate waves from a southerly direction some short-term northward alongshore movement of sand might be expected for the duration of the storm. Seasonal profile changes have been observed (20, 23). The heavy mineral analyses of Cherry (5) in Drakes Bay indicate that little or no sand is moving around Point Reyes into Drakes Bay. In other words, the sand beaches along the shore of Drakes Bay appear to be in stable equilibrium and only experience movement of minor importance during short periods when southerly storms exist.

Bolinas Bay. This bay is similar in size to Bodega Bay. A lagoon exists behind a sand spit and connects with the bay through a natural tidal inlet (Figure 10). The headland behind which the bay is formed is non-dioritic (being a hard shale reef on edge). The orientation of the upcoast shoreline of high shale cliffs is not conducive to the formation of sand dunes in this locality (27). As in Drakes and Bodega Bays the location of the entrance is forced as far westward as high ground permits. Previous studies have shown that the area of inlet to Bodega lagoon is a function of the tidal volume of the lagoon (16). No stabilization of the entrance has been attempted; however, such work has been proposed on several occasions. No data on the character of littoral sand movement are available for this area

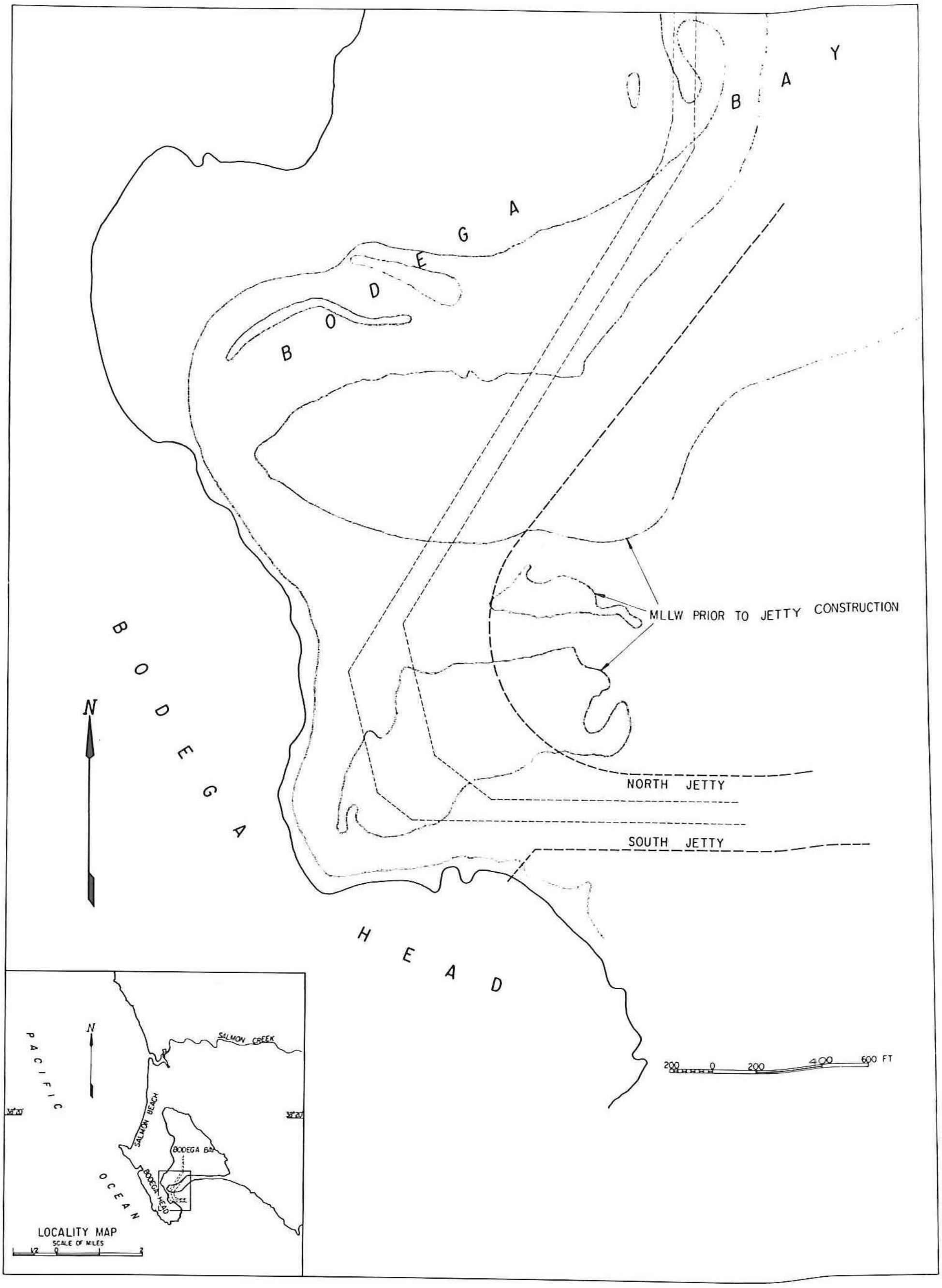


Figure 8. Entrance to Bodega Harbor showing natural and jettied conditions

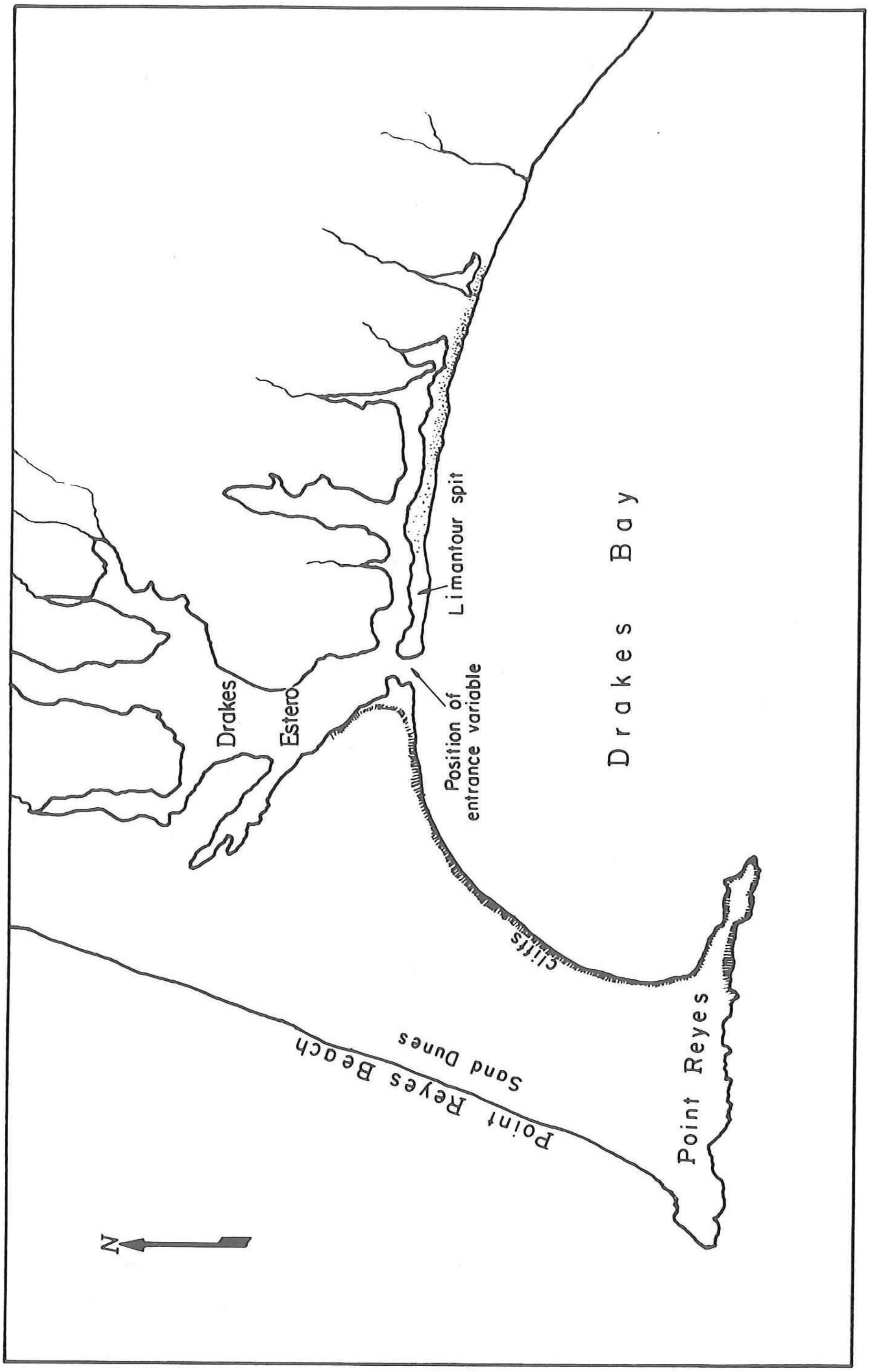


Figure 9. Geographical features of Drakes Bay

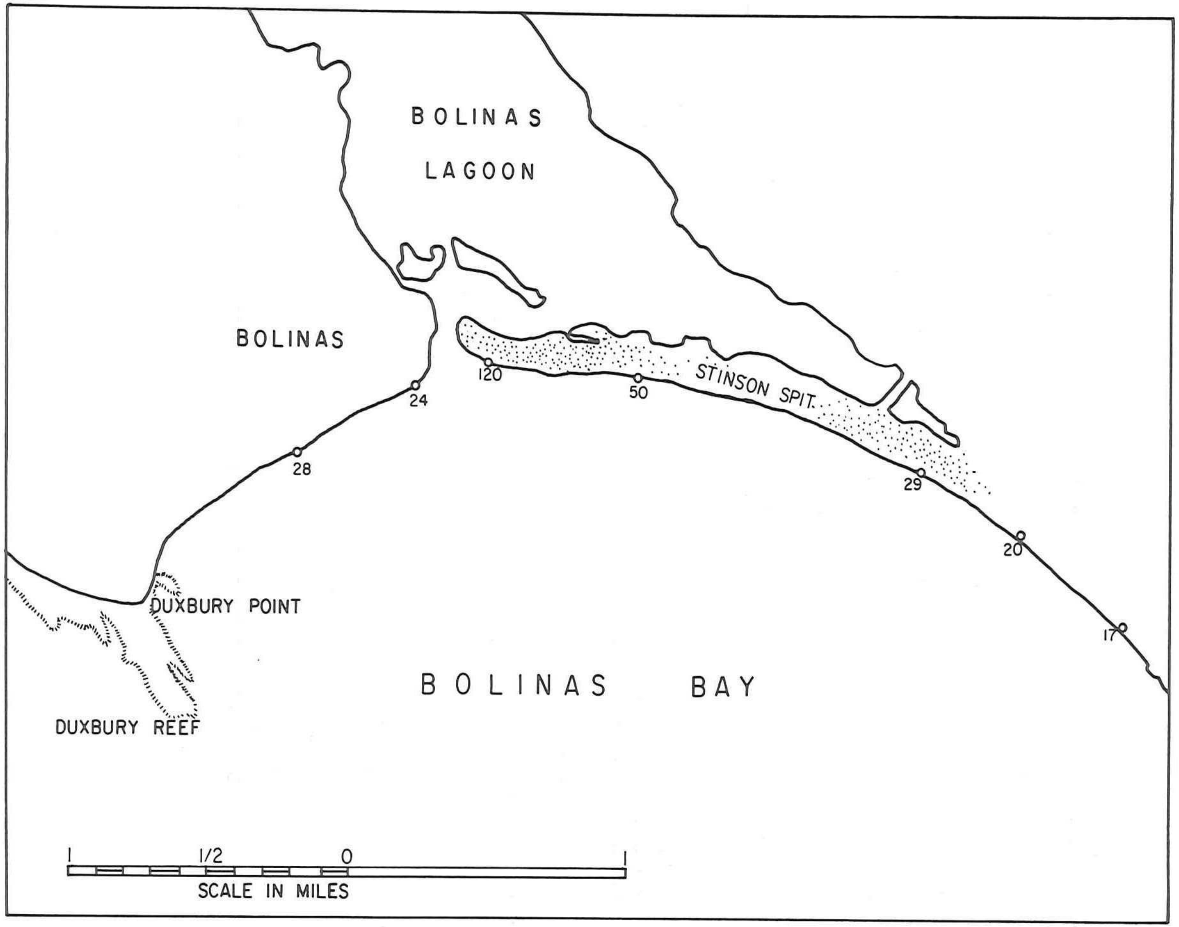


Figure 10. Geographical features of Bolinas Bay with thorium concentrations shown along the shoreline

(except for seasonal changes (21, 23)), but the heavy mineral studies of Moore (13) indicate that very little nearshore sand transport appears to occur in this area; however, as in the case of Drakes Bay (Figure 4) the thorium distribution along the shoreline of Bolinas Bay as shown in Figure 10 indicates a prevailing drift southward.

Half Moon Bay. This bay is similar to the other hooked-bays along the coast except that the back beach geology is such that no lagoon or sand dune system exists. The physical features of the shoreline of this bay in its natural state are well documented in studies by Krumbein (11) and Bascom (1). These studies demonstrated the now accepted concept of variation of beach slopes and grain size with wave exposure. In 1959-60 the breakwater system indicated in Figure 11 was constructed. Since completion of the breakwater, some undesirable wave action during southerly storms has been experienced at the boat facilities directly opposite the opening in the breakwater. A model study of this harbor was made in 1965 (26) which showed that an extension of the west breakwater would be necessary to correct the wave action problem (See Figure 11 for recommended extension). During and following construction of the east breakwater some sedimentation problems occurred at the root of the breakwater due to the alteration of the local wave pattern by refraction and diffraction effects. No sedimentation problems, however, have occurred along the west breakwater or at the existing harbor entrance in the years since construction of the breakwaters - thus, indicating that littoral drift in this vicinity is non-existent or extremely small. This appears to be confirmed by the small variation of thorium concentration along the shoreline of Half Moon Bay as shown in Figure 11.

San Francisco Bar. A predominant feature of the hydrography off the Golden Gate is the large crescent-shaped bar shown in Figure 12. The position of the Bar appears to be in approximate equilibrium as a result of the prevailing wave action which tends to move sediment eastward toward the Golden Gate and the tidal currents which occur during ebb flows from San Francisco Bay and tend to move sediment westward. Actually the position of the Bar fluctuates as indicated by the horizontal movement of the Bar from 1855 to 1956 (Figure 12) measured by changes in the centroids of sections using the -60 MLLW as the base level (24). Three navigation channels cross the Bar, but only the east-west main ship channel requires maintenance dredging to insure a sufficient depth (50 ft.) for large ships. Following is a summary of the annual amounts of material dredged from this channel in the last 10 years (25).

Year	Cubic Yards	Year	Cubic Yards
1955	1,429,500	1960	763,000
1956	309,000	1961	875,000
1957	595,000	1962	1,145,000
1958	626,000	1963	842,000
1959	3,840,000	1964	581,000

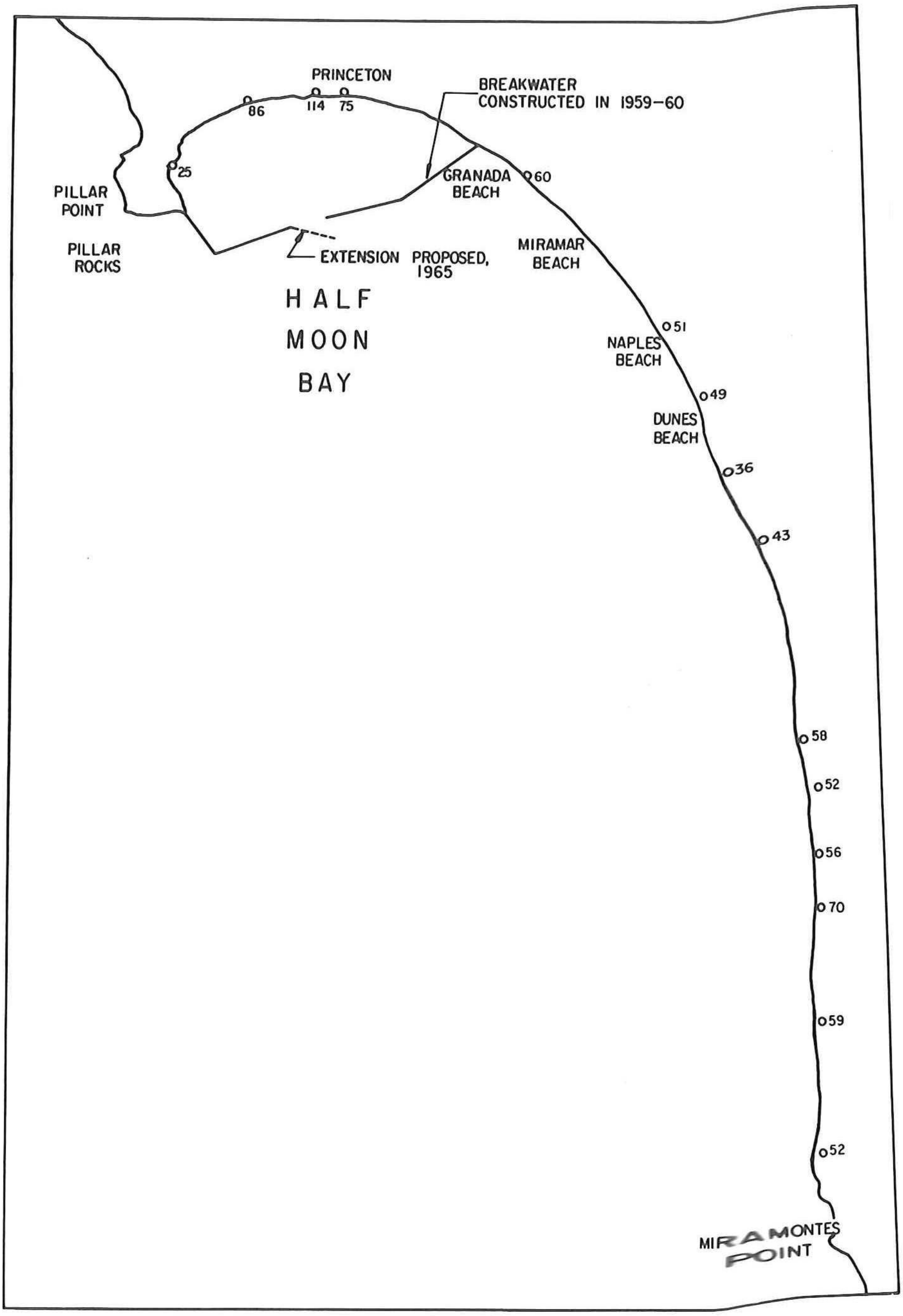


Figure 11. Geographical features of Half Moon Bay with thorium concentrations shown along the shoreline

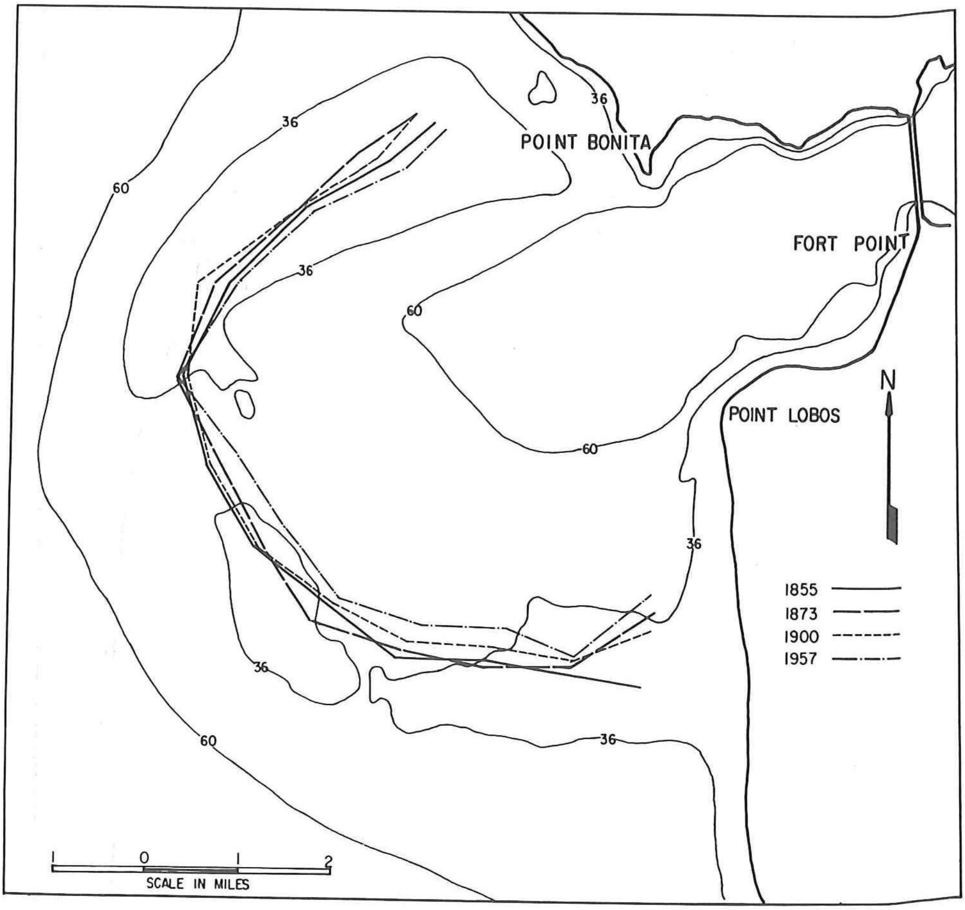


Figure 12. Estimated movement of San Francisco Bar (see Ref. 24)

The above figures are not necessarily a true indication of the shoaling of the Bar channel. Because of weather conditions and the limited availability of a dredge each year, the Bar channel is not always dredged to project dimensions. In addition, prior to 1959 only 1,000 feet of the authorized 2,000 ft. width channel was maintained to the 50 ft. width. In 1959 the channel was deepened to 50 feet for the entire 2,000 ft. width - hence, the relatively high amount dredged that year as indicated in the above table.

In view of the fact that there is no major source of materials of the sand sizes being fed into the littoral zone in the Russian River-Half Moon Bay reach and that the various analyses of sediment characteristics indicate a relatively small rate of littoral drift, it therefore appears that the material which shoals the main ship channel is derived from the material comprising the Bar itself as a result of local currents and wave action.

CONCLUSIONS

For the reach of shoreline under study a consideration of (a) the distribution of both heavy and light minerals in the nearshore zone, (b) the possible sources of sediment contribution, (c) the planform of the coastline, and (d) the history of sedimentation at harbor entrances all indicate that the transport of nearshore sediments is relatively small.

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