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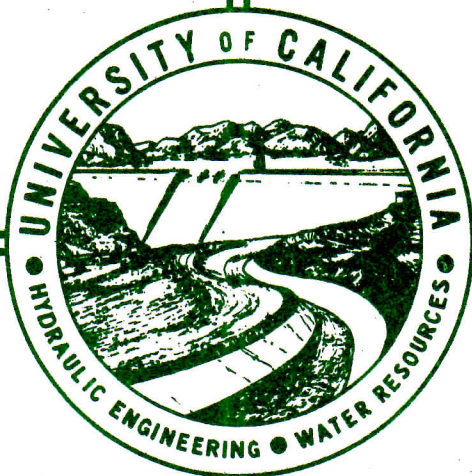
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THE EROSIONAL AND DEPOSITIONAL HISTORY OF THE COAST OF NORTHERN CALIFORNIA

by

CLAUDE R. MINARD, JR.



HYDRAULIC ENGINEERING LABORATORY
WAVE RESEARCH PROJECTS

UNIVERSITY OF CALIFORNIA
BERKELEY

University of California
Hydraulic Engineering Laboratory

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THE EROSIONAL AND DEPOSITIONAL HISTORY OF A
PORTION OF THE COAST OF NORTHERN CALIFORNIA

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Claude R. Minard, Jr.

Berkeley, California
September, 1964

ABSTRACT

A previous investigation of the beach and nearshore sands occurring along the coast of Northern California between the mouth of the Russian River and the southeastern end of Drakes Bay has demonstrated the presence of seven distinct areas characterized by particular assemblages of heavy minerals ("mineralogic provinces"). The present work substantiates the theory that these "mineralogic provinces" are related not only to the present cycle of erosion and deposition but also to a prior cycle (or cycles).

Neither present day littoral transport of sand nor the local contribution of detritus can adequately explain the current distribution of the "mineralogic provinces". In many cases, sands containing a preponderance of heavy minerals derived from the Franciscan Formation are found in areas in which present day local sources for such minerals do not exist while, at the same time, adjacent areas are characterized by beach and nearshore deposits which contain little or no Franciscan-derived detritus. The most logical explanation for these occurrences involves an earlier period of lower sea level which promoted the erosion of Franciscan rocks and the downcoast transport of the resulting detritus. This low stand of sea level was followed by the re-advance of the sea (to its present level) and the consequent erosion of primarily non-Franciscan rocks. Recent erosion has resulted in the local deposition of non-Franciscan detritus (principally dioritic material) and the masking or drastic dilution of many of the Franciscan-derived sediments brought in by earlier littoral drift.

The fact that not all of the earlier sands have been masked by the products of recent erosion can largely be attributed to the relatively minor amount of erosion and contribution of sediment which appears to have taken place since the re-advance of the sea to its present level. The occurrence of older, pre-existing wave-cut beaches and cliffs in association with older beach and dune deposits indicates that much of the present coastal configuration was sculptured before the present cycle of erosion. The widespread occurrence of older, ferruginously-cemented dune sands of Franciscan-derived mineralogy fronting pre-existing wave-cut cliffs not only substantiates the supposed downcoast transport of sands eroded from the Franciscan during a lower stand of sea level but also demonstrates that present day coastal erosion, in many cases, has not proceeded to the point reached during an earlier period.

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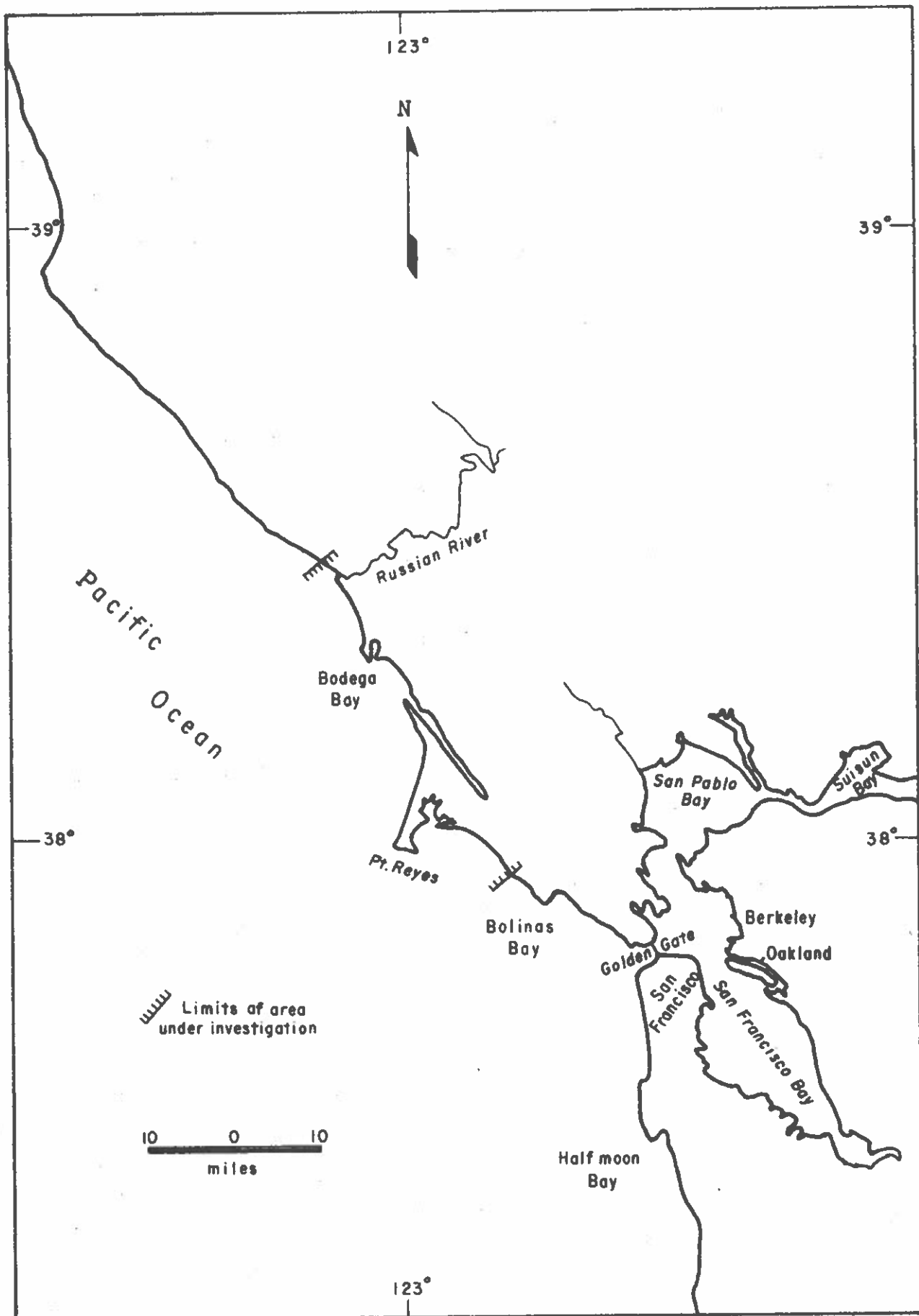


FIG. 1 LOCATION OF THE AREA UNDER INVESTIGATION

I. Introduction

The sands occurring along the coast of Northern California from the mouth of the Russian River to the southeastern end of Drakes Bay (Fig. 1) contain essentially separate, distinct assemblages of heavy minerals ("mineralogic provinces"). The main purpose of this report is to present the results of a preliminary investigation of the relationship between these sands and sands which were derived from present and past local sources and which possibly were involved in littoral drift during the past. These results are based upon a consideration of both geomorphologic and mineralogic evidence.

In addition to a general reconnaissance of the geologic and geomorphologic conditions in the area under investigation approximately eighty samples were collected of representative local rock types, soils, stream sediments, and dune sands; some additional beach samples were also collected in order to augment existing beach information. The rock and soil samples were generally taken as "channel" samples which included both weathered and unweathered material. The stream, dune, and beach sands were generally taken as "spot" samples by means of a three-inch diameter steel pipe, which extracted a core approximately ten inches long.

After disaggregation, washing, and sieving of the samples, the heavy minerals were separated by the use of bromoform; these minerals were mounted in Canada balsam and analyzed under the petrographic microscope. In order to provide results which were comparable with those of previous investigations in the area, only the minerals occurring in the size-fraction between 61 and 250 microns were examined. Mechanical analyses were also made of most

of the samples.

The conclusions reached in this report are tentative but they do point to the strong possibility of past littoral drift as an important influence upon the present distribution of sands off the coast of portions of Northern California. The role played by local contribution of sediment during the present and the past will be the subject of more intensive field study in the area under investigation. It is hoped that a clearer picture of the geomorphic development of the area might shed more light on the problem of the source (or sources) of the sands presently occurring along the coast.

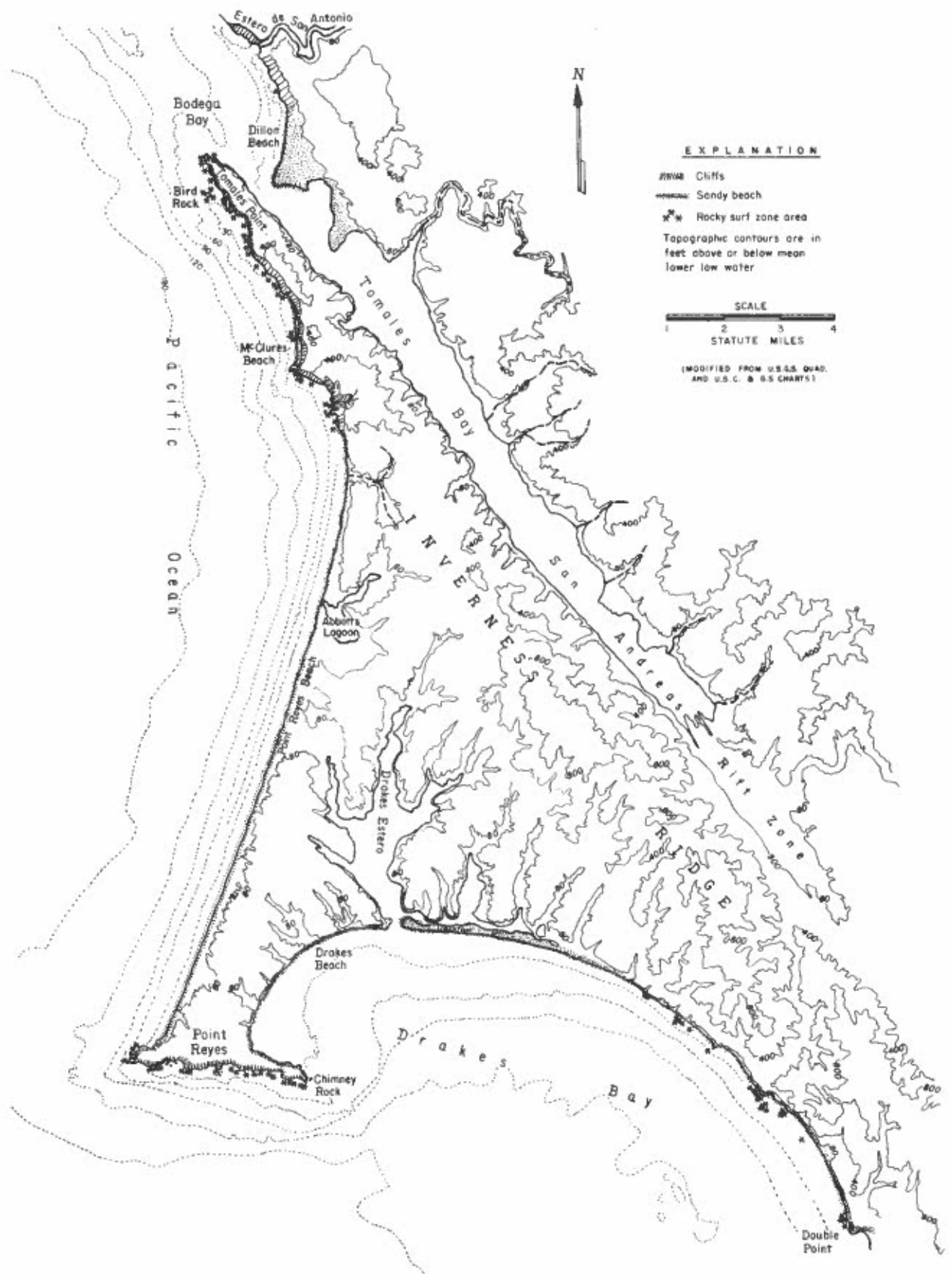


FIG.2 COASTAL PHYSIOGRAPHY OF THE TOMALES POINT - DRAKES BAY AREA

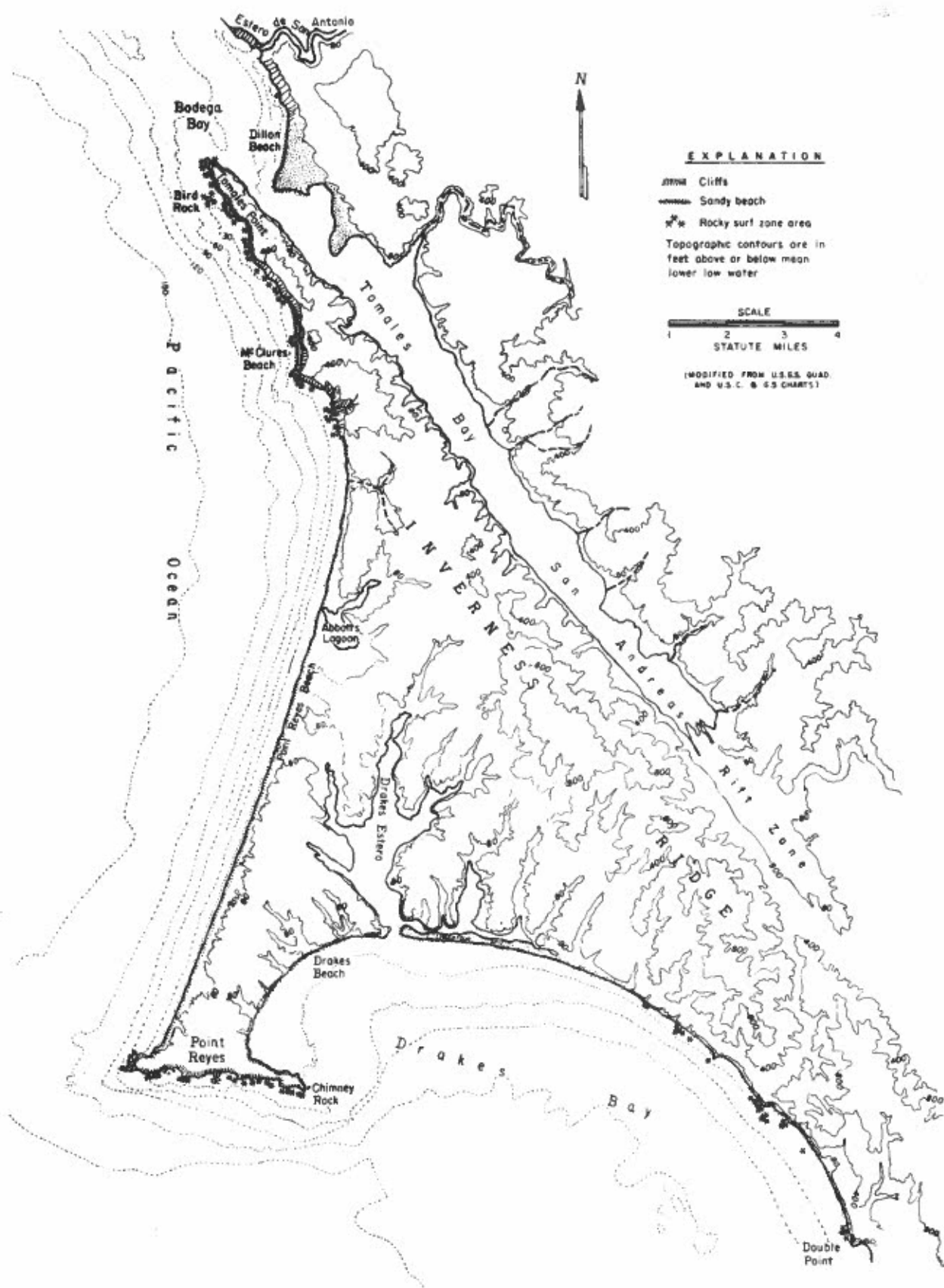


FIG 2 COASTAL PHYSIOGRAPHY OF THE TOMALES POINT - DRAKES BAY AREA

II. General Setting

The pronounced northwesterly trend of much of the coast line between the mouth of the Russian River and the southeastern end of Drakes Bay (Figs. 2 and 3) reflects the influence of the San Andreas Fault Zone, the principal structural lineament along the coast of Northern California. This fault zone not only influences the trend of the coast line but also serves to separate the area under investigation into two distinct geologic provinces (Fig. 4 and 5). The area immediately adjacent to the eastern margin of the fault zone is composed almost entirely of rocks of the Franciscan Formation of Jurassic and Cretaceous age with a somewhat localized and discontinuous exposure of sedimentary rocks of the Pliocene Merced Formation. The Franciscan is composed primarily of poorly sorted sandstone (rich in rock fragments, quartz, and feldspar) and subordinate amounts of shales, cherts, altered volcanic rocks, and low grade metamorphic rocks (notably glaucophane schists). The Merced Formation contains an abundance of gravelly conglomerates and medium-grained sandstones both of which were derived mainly from Franciscan rocks.

The area to the west of the San Andreas Rift contains exposures of dioritic rocks of Mesozoic age and Tertiary sediments which range from Paleocene conglomerates, Middle Miocene, shales and sandstones, to Upper Miocene siltstones, mudstones, and silty sandstones. In the general region to date, no exposures of Franciscan rocks have been reported west of the fault zone and no dioritic rocks have been recorded on the east side of

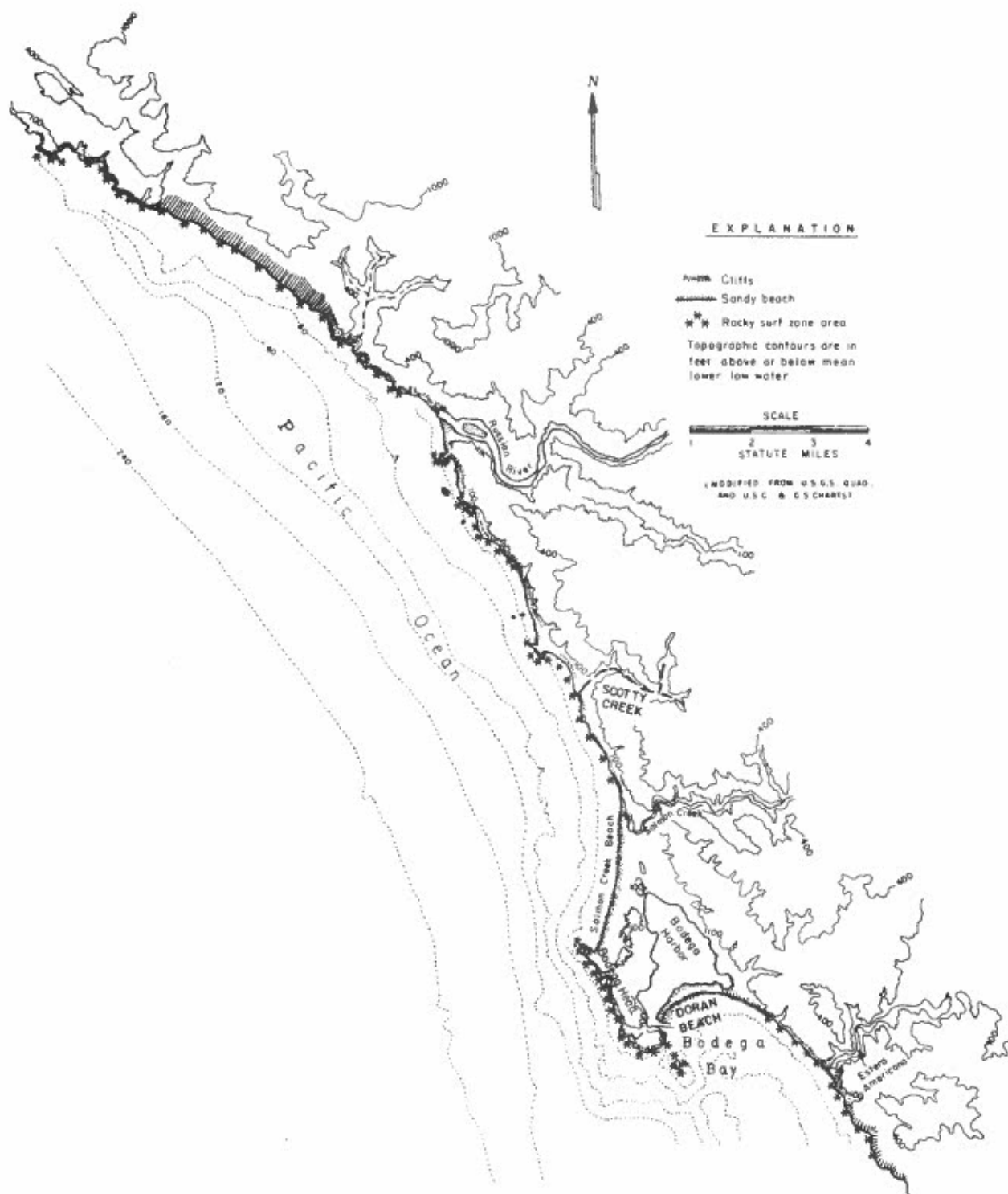


FIG.3 COASTAL PHYSIOGRAPHY OF THE RUSSIAN RIVER-BODEGA HEAD AREA

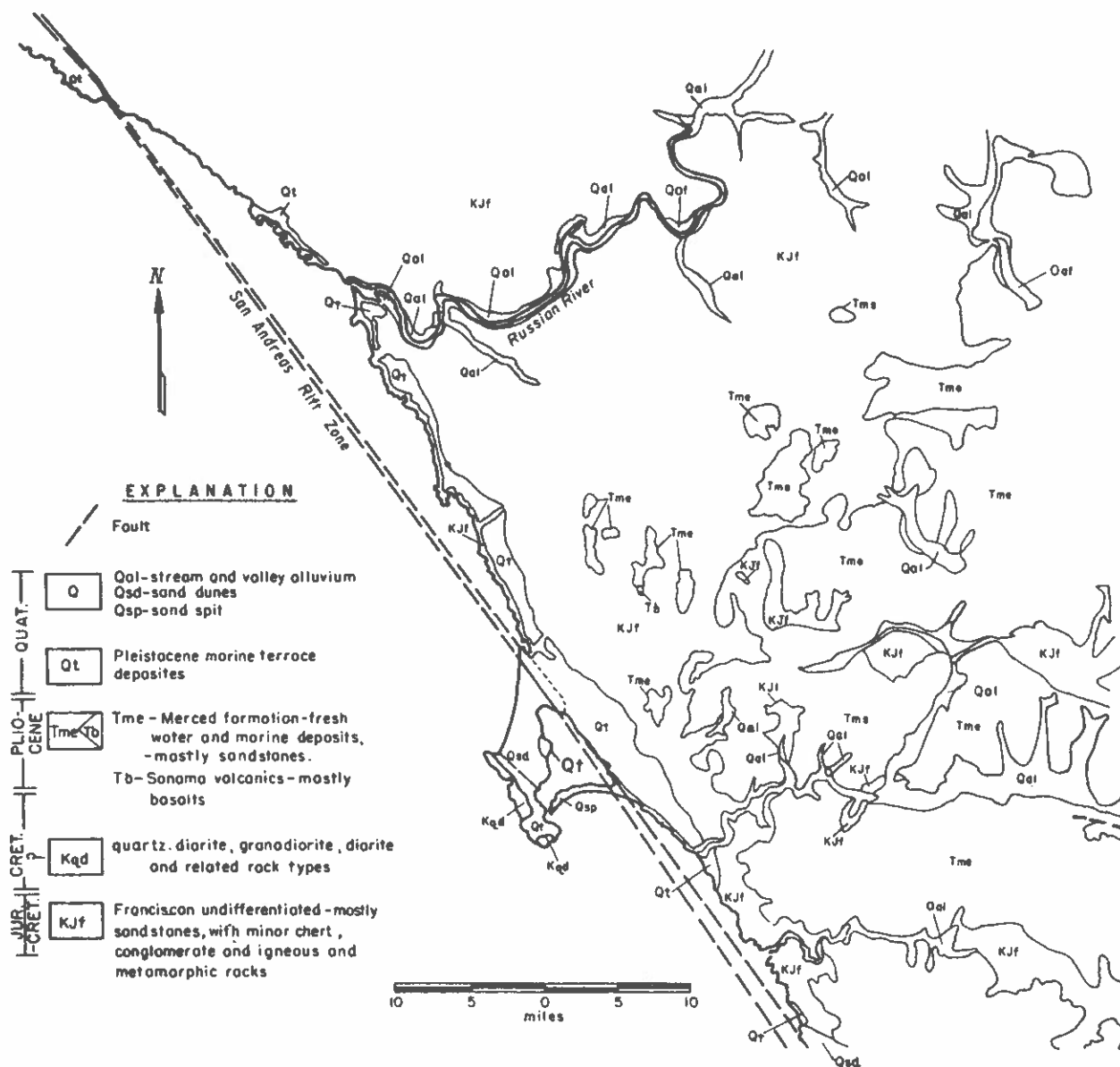


FIG.5 GEOLOGIC MAP OF RUSSIAN RIVER - BODEGA HEAD AREA (Modified after Johnson, 1934)

the rift.

The area under investigation is characterized by rather flat-topped hills and ridges cut by widely-spaced steep-sided valleys. The coast line itself is commonly cliffed and generally backed by relatively broad flat areas. The lower flat areas represent Quaternary marine terraces (many of which contain terrace sands and gravels) but many of the flat tops of the higher hills and ridges might be related to earlier periods of erosion.

With the exception of the Russian River, there are few relatively large streams in the area and these are characterized by short, widely-spaced tributaries, low volumes of flow, alluviated valleys, and estuarine mouths. The streams which drain the area on the eastern side of the fault zone typically have meandering courses with gentle gradients (on the order of eight feet per mile). The streams to the west of the fault zone appear to be relatively young consequent streams which have comparatively straight courses and steeper gradients (often up to several hundreds of feet per mile).

Present day subaerial erosion (other than processes associated with marine erosion such as cliff recession) appears to be limited in most cases to a general slight intrenching of streams into their valley fill and the rather widespread occurrence of small landslides and slumps in relatively incompetent material. Over the general area, the rocks are poorly exposed and are usually covered by residual soil of varying depths. Locally, dune sands cover fairly extensive areas. The only large exposures of fresh rock

occur along the cliff faces on the present day coast line.

Although in gross outline the coast sub-parallel the northwesterly trend of the San Andreas Fault Zone (with the Point Reyes Peninsula forming the only marked departure from this trend), in detail the coast is a complex of sections (Figs. 2 and 3) whose orientations and other characteristics reflect the varying influences of erosional, depositional, and tectonic processes. On the basis of both geologic and geomorphologic factors, the various sections which make up this portion of the coast can be subdivided into three main groups - each group consisting of areas which exhibit certain very marked similarities to one another. These three groups are based on consideration of the following factors: (1) The orientation of the shore line¹ and of the coast line¹ and the relation of these orientations to one another, (2) The orientation of the shore line in relation to the present day pattern of distributions of wave energies, and to the angle of approach of pre-dominant swell, (3) The nature of the shore deposits, (4) The character of the coast line - its topographic expression and constituent rock types, and (5) The character of the foreshore area.

The first group of coastal sections consists of Salmon Creek Beach, Doran Beach, and Dillon Beach (Figs. 2 and 3) and is characterized by the following conditions: (1) The shore line departs markedly from the trend

1. In this report a distinction is made between the terms coast line and shore line. The former is considered to mark the contact between the land and beach deposits or between land and sea if no beach deposits exist. The latter term is used to denote the contact between the sea (at mid-tide) and any existing beach deposits.

of the coast line, (2) The shore line has adjusted to the present day pattern of wave energy distributions and is oriented parallel to refracted fronts of the predominant swell, (3) The beaches are broad accumulations of sand which form rather continuous smoothly curving shore lines (in detail the shore line usually exhibits local irregularities, particularly cusps) and often form a bar or a spit, (4) The coast lines varies in topographic expression and in nature of types of rocks involved; the coast line is often separated from the shore line by a lagoon, and (5) The foreshore is typically sandy and essentially devoid of rocks, rocky terraces, and other obstructions.

The third group of coastal sections is comprised of the area between the mouth of the Russian River and Salmon Creek, Bodega Head, the area between Doran Beach and Dillon Beach, most of Tomales Point (particularly excluding McClures Beach), Point Reyes, and the rocky area along Drakes Bay south and east of the proximal end of Limantour Spit (Figs. 2 and 3). These areas are characteristically represented by the following conditions: (1) The shore line and the coast line essentially parallel one another; in many cases the shore deposits are absent or only very locally present, (2) The orientations of the shore line and the coast line bear no close relationship to the present pattern of distribution of wave energies, or to the orientation of the refracted fronts of the predominant swell, (3) The beaches are often absent or restricted to pocket coves; when present, the beaches are narrow and discontinuous; the beach material is often shingle rather than sand, (4) The coast line is cliffed and highly irregular

in configuration; the cliffs are usually cut into resistant rocks, and
(5) The foreshore is typically rocky with prominent wave-cut benches, stacks, headlands, and other features associated with the differential erosion of relatively resistant rocks.

The third group of coastal sections contains those areas in which the coast lines are subjected to concentrated wave attack and therefore are areas of net contribution of sand to the littoral zone. The second group is composed of areas which appear to be more-or-less in a state of equilibrium as regards the transfer of sand to and from the littoral zone. The areas in the first group of coastal sections are those which, if not receiving large quantities of sand at the present, were the sites of large accumulations of sand in the not too distant past.

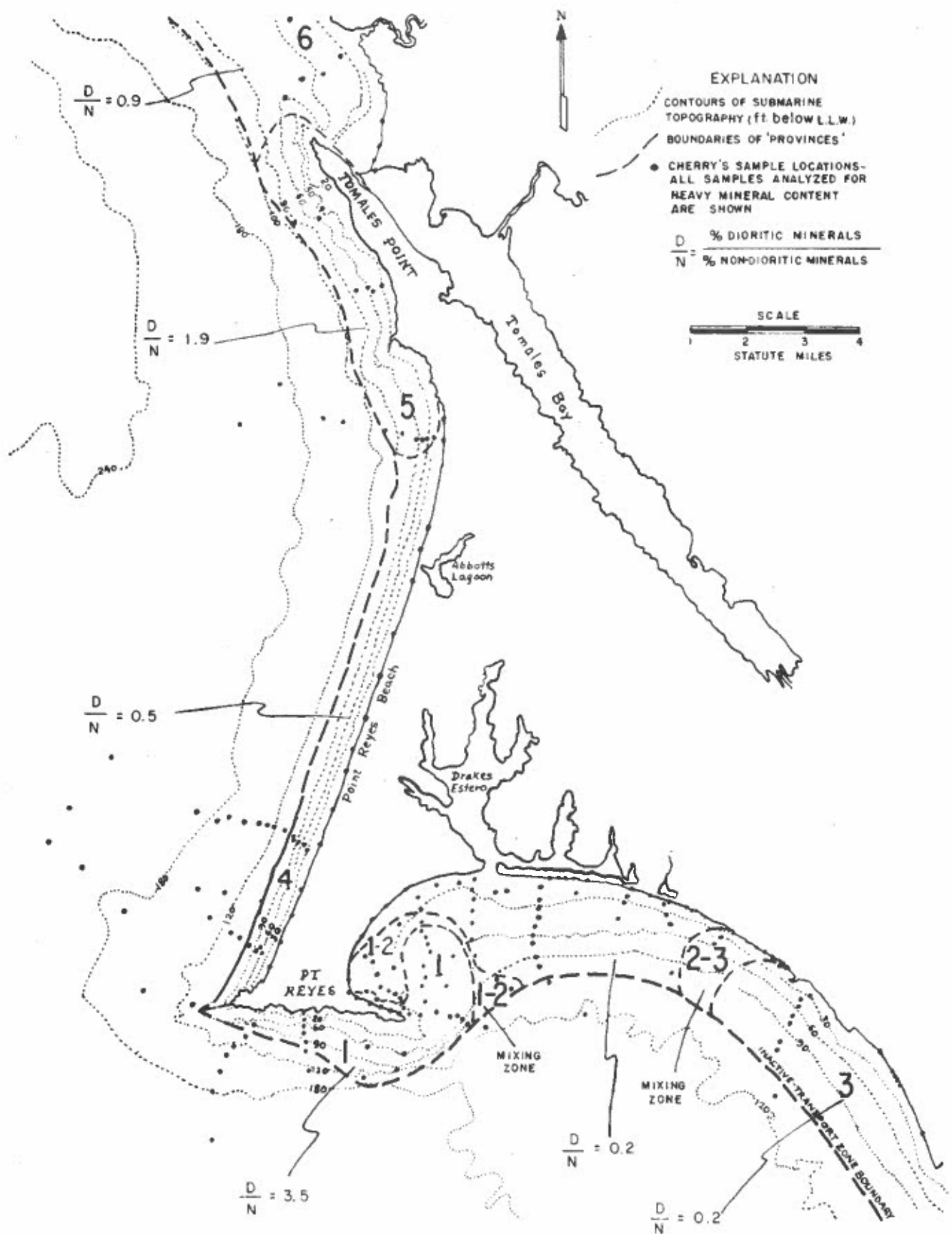


FIG.6 HEAVY MINERAL DISTRIBUTION IN THE TOMALES POINT-DRAKES BAY AREA
(Modified after Cherry, 1964)

III. Mineralogic Provinces

In the work, Sand Movement along a Portion of the Northern California Coast, (Cherry, 1964) which provides the basis for much of this report, seven principal, distinct mineralogic² provinces (Figs. 6 and 7) were described along the coast between the mouth of the Russian River and the southeastern end of Drakes Bay. These seven provinces were distinguished on the basis of gross differences in the heavy mineral composition³ of the sands occurring along the coast (Table I). The constituent minerals generally fell into three main categories: (1) The "dioritic" minerals - dark green hornblende, sphene, and apatite - which were derived from the diorite bodies at Bodega Head, Tomales Point, and Point Reyes, (2) The so-called "non-dioritic" minerals which were principally derived from the Franciscan or sources related to the Franciscan - augite, metamorphic hornblende, glaucophane, actinolite - tremolite, lawsonite, hypersthene, garnet, and carbonate (ankerite) (carbonate, garnet, and to some extent hypersthene appear to come from other sources in addition to those related to the Franciscan), and (3) The ubiquitous zircon and epidote plus other minerals which were considered as essentially non-diagnostic (the

2. Unless otherwise specified, the terms "mineral" or "mineralogic" will refer exclusively to heavy minerals.
3. The heavy mineral composition was based upon the percentages of different species of "non-opaque" (translucent) heavy minerals (excluding biotite and chlorite). Although the opaque minerals were counted, they were not identified and did not enter into the percentages.

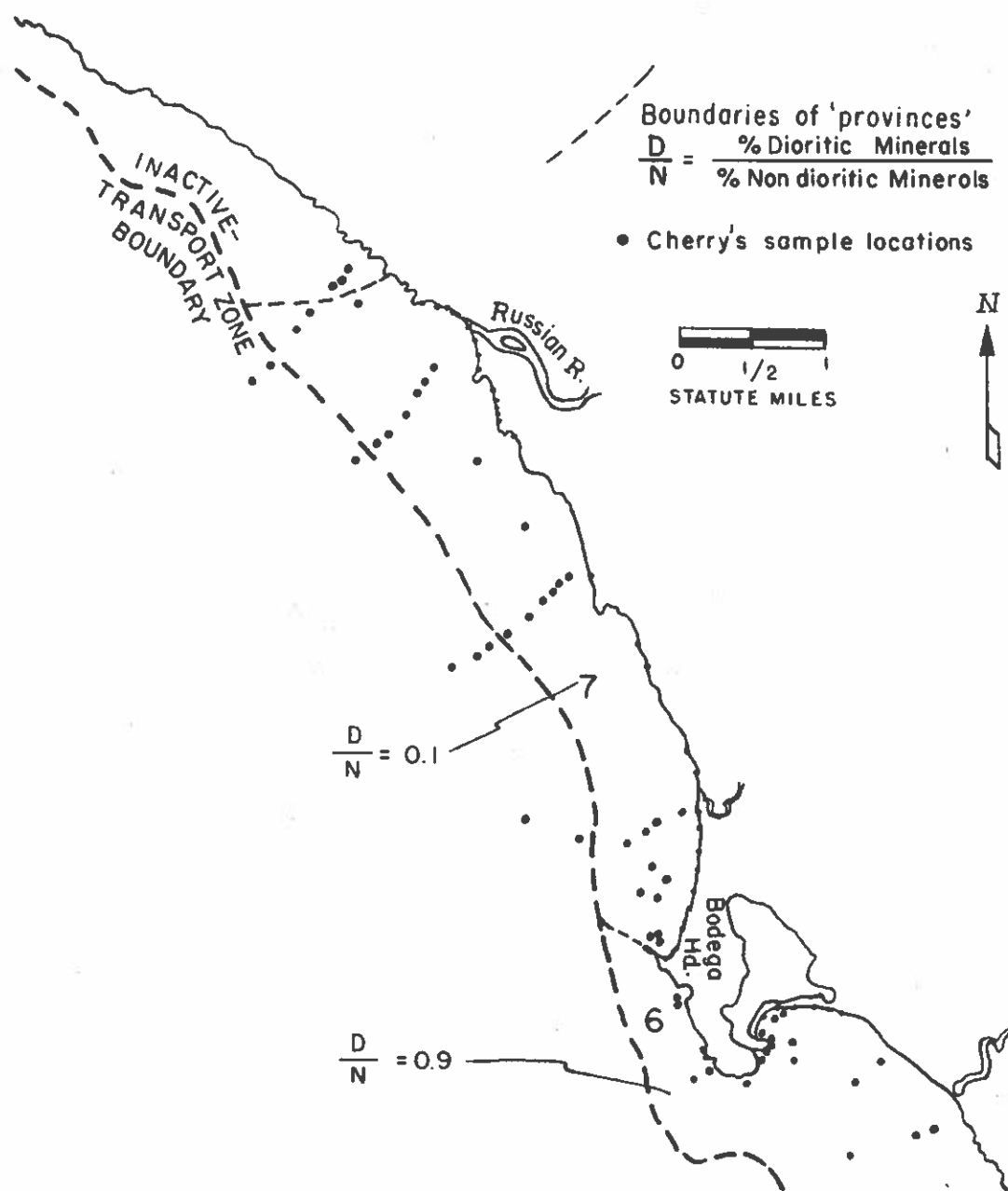


FIG. 7 HEAVY MINERAL DISTRIBUTION IN THE RUSSIAN RIVER - BODEGA HEAD AREA
(MODIFIED AFTER CHERRY, 1964)

Column No.	1	2	3	4	5	6											7	8			9				
Province Number	No. of samples analysed	Definition * of Provinces	No samples in Definition	No samples two hornblendes distinguished	X = mean s = stand. dev. R = Range	Non - opaques											Opakes and Others	Non - Opaque groups			RATIO OF DIORITIC MINERALS TO NON-DIORITIC MINERALS % Dioritic / % Non-Dioritic				
						Total hornblende	pale green hornblende	dark green hornblende	sphene	augite	glaucophane	tremolite - actinolite	garnet	zircon	hypersthene	epidote		ankerite	lawsonite	apatite		others	Dioritic	Non-diorite	All others
1	35	Dio >65	29	35	X S	420 11.1	0 0	420 11.1	31.0 9.2	6.4 3.4	2.2 1.8	1.9 2.4	4.8 2.5	4.0 2.7	0.2 1.1	2.2 1.7	1.2 3.2	0.5 0.8	1.4 1.7	2.0 1.9	473 202	72.5 8.9	20.8 7.0	6.8 3.3	3.5
2	62	Dio <20 Ank <10	58	26	X S	11.5 50	3.7 1.7	8.2 2.3	6.9 3.4	26.4 8.3	10.0 4.6	11.6 5.9	7.9 4.8	6.2 4.7	1.9 1.5	7.5 3.8	2.4 3.3	3.3 2.6	0.6 0.9	3.9 2.5	636 228	15.5 4.8	66.4 8.2	17.9 7.3	
3	14	Ank >32	13	14	X S	75 79	2.6 2.5	4.9 5.7	4.8 1.4	8.3 4.8	3.1 1.4	5.5 2.8	5.5 5.2	9.3 7.2	0.6 1.2	2.9 1.9	46.9 13.5	1.9 2.5	1.3 1.7	2.3 2.8	569 399	12.0 5.6	74.3 8.5	14.6 7.6	0.2
4	34	Dio <40 Gar. <20	30	20	X S	206 7.4	5.5 6.0	15.1 3.7	11.4 3.9	16.7 6.0	9.6 3.6	9.2 4.1	10.4 5.2	4.5 3.0	2.0 1.7	7.0 3.7	2.4 2.4	3.1 2.4	1.0 1.3	2.5 2.4	627 326	27.8 7.6	58.4 7.8	14.0 5.8	
5	13	Dio >47 Non-D <36	11	13	X S	35.6 9.8	4.2 2.8	31.4 9.0	24.5 7.4	8.5 2.6	2.8 2.5	4.1 2.7	5.9 4.3	3.9 4.7	0.9 1.0	6.1 3.3	2.5 1.6	1.6 2.1	2.5 1.8	1.2 1.7	441 216	58.3 7.2	30.5 4.9	11.2 5.2	1.9
6	32	Non-D >36	27	20	X S	44.2 12.9	4.7 2.2	39.6 12.5	6.7 4.3	13.0 6.5	10.6 4.3	12.6 5.6	1.8 1.7	1.5 1.6	0.7 1.0	3.0 2.2	3.2 2.7	1.8 1.6	0.5 0.7	1.5 1.5	325 100	45.6 12.5	48.4 11.6	5.9 3.4	
7	64	Non-D >70 Ank <10	60	60	X S	10.6 4.5	7.3 3.3	2.8 1.5	2.3 1.8	25.2 7.8	18.5 5.5	19.2 7.2	3.3 3.7	1.6 2.1	1.6 1.9	7.3 4.6	2.1 2.1	3.7 3.2	0.3 0.6	4.0 3.1	692 329	6.2 6.4	80.4 7.4	12.9 5.8	0.1

* Abbreviations } Dio = Dioritic group = dark green hornblende + sphene + topatite Ank = Ankerite Gar = Garnet All others = zircon + epidote + others and groups } Non-D = Non dioritic group = pale green hornblende + augite + glaucophane + tremolite - actinolite + garnet + hypersthene + ankerite + lawsonite

TABLE 1 SUMMARY OF THE HEAVY MINERAL COMPOSITIONS OF THE TRANSPORT ZONE PROVINCES*
(*Province' locations shown in figures 6 and 7)
(MODIFIED AFTER CHERRY, 1964)

association of high concentrations of carbonate and high percentages of zircon relative to the other Franciscan-derived minerals appears to be indicative of detritus derived from the Middle Miocene shales). The seven mineralogic provinces are listed in table 1.

How and why did these various distinct mineralogic assemblages come to occur in their present locations and from where were they derived? In order to answer these questions, three different explanations of possible processes can be considered. The first explanation involves the assumption that sand continually moves downcoast from the mouth of the Russian River. If such were 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) were sufficiently large so as to cause (1) "flooding out" and masking of the mineral assemblage carried along by the sands moving in from adjacent areas upcoast or (2) 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.

An alternative explanation is that the mineralogic provinces exist because there is little or no downcoast transport of sand at the present from the mouth of the Russian River or from any other source. 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.

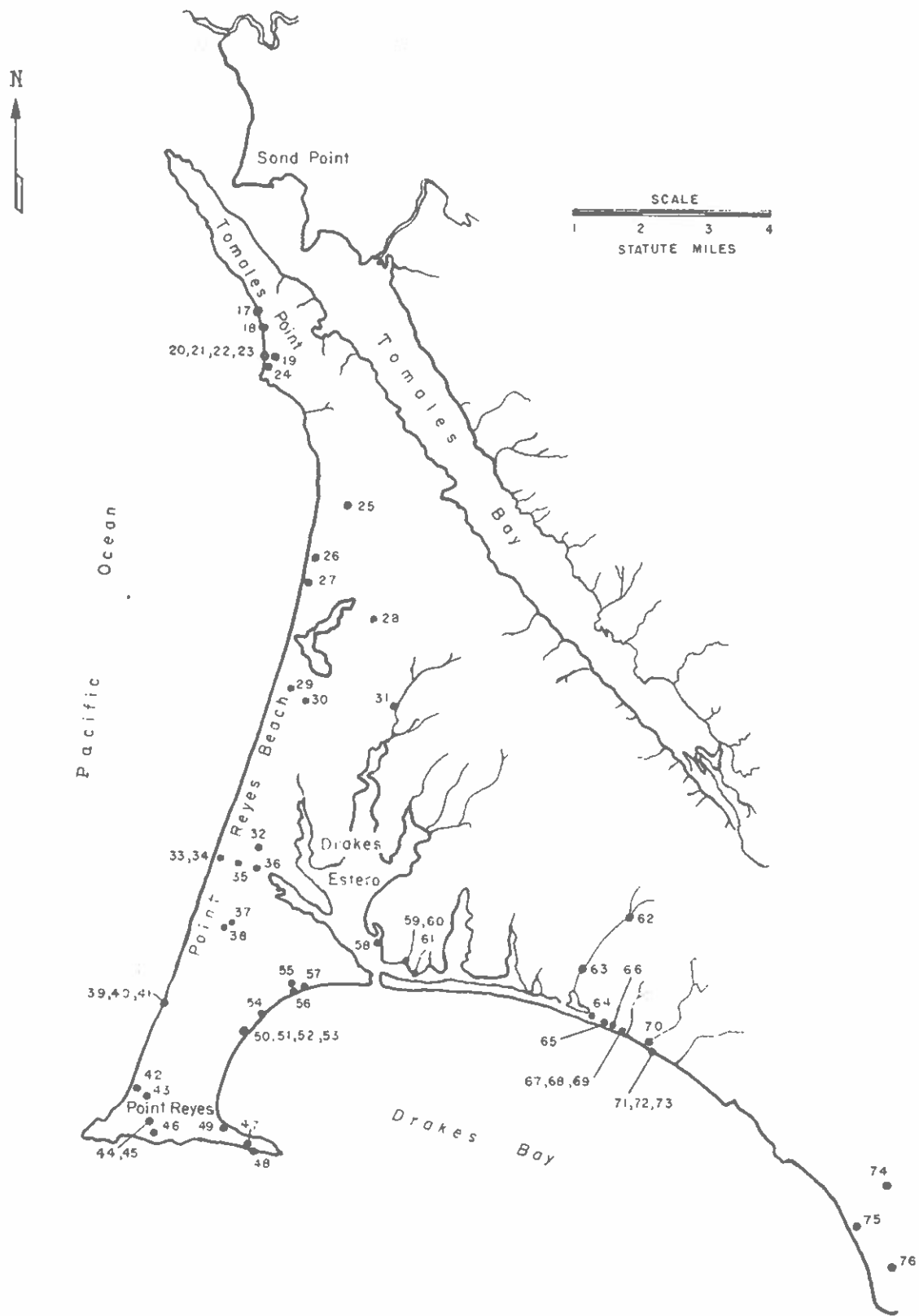


FIG. 8 SAMPLE LOCATIONS IN THE TOMALES POINT- DRAKES BAY AREA

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 that 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.

No matter which of the three explanations most closely approximates actual conditions, each one involves processes which effectively rule out the possibility of continuous movements 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. Since the existence of the distinct mineralogic provinces argues against the relative importance of the present day littoral transport of sand, it is necessary to consider the evidence provided by the individual provinces in order to reach conclusions concerning the most logical explanations for these present distributions of sand along the coast. (See Figures 8 and 9 for sample locations and Appendix "A" for mineralogic and mechanical analyses data).

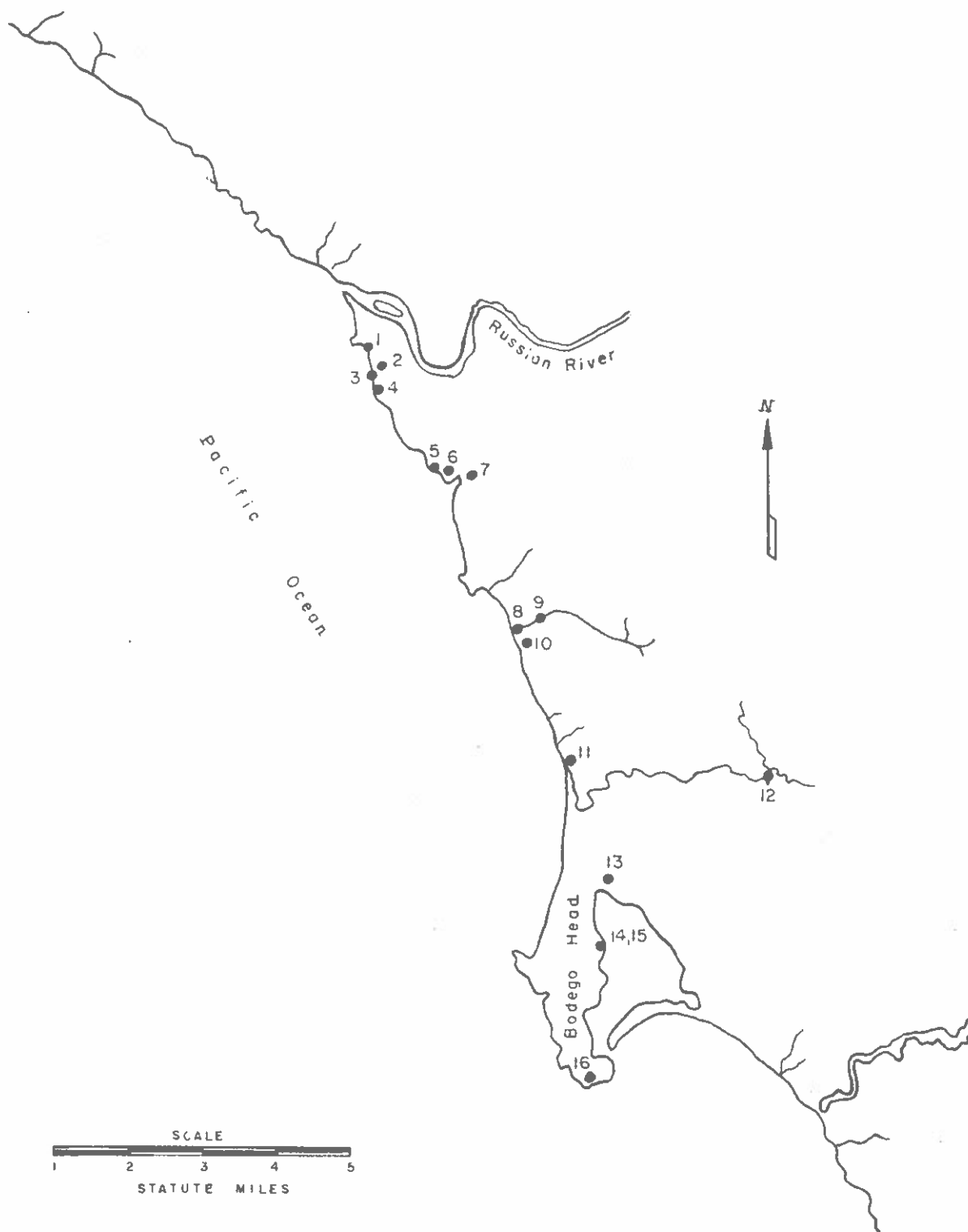


FIG. 9 SAMPLE LOCATIONS IN RUSSIAN RIVER-BODEGA HEAD AREA

IV. Evidence From the Local Areas

Along the coast between the mouth of the Russian River and the northern end of Bodega Head (Cherry's province 7) the beaches are typically backed by cliffs in Franciscan rocks. These cliffs are usually topped by a thin layer of marine terrace sands and gravels of Franciscan derivation. The streams which empty into the ocean in this area (including the Russian River) carry sands which contain Franciscan-derived mineral assemblages. As would be expected, the beach and offshore deposits exhibit an almost completely "non-dioritic" composition.

Many small headlands and points and numerous rocks, islands, stacks, and arches provide sites for cliff erosion although many of the cliffs are somewhat protected by beaches. In these protected areas small dunes (sometimes stabilized by vegetation) occasionally occur and the cliffs are usually fronted by fairly well indurated stabilized colluvium or an inter-layering of colluvial and dune materials. No large landslides were observed along the coast in this area.

The headlands and other prominences appear to be formed mainly from resistant rocks and the less resistant rocks (typically shales or rocks which have been highly faulted) generally appear to have been eroded back to form the sites for pocket beaches. The occurrence of dunes and stabilized colluvium indicates that wave attack has only limited effectiveness in causing present day cliff erosion. Only minor streams (excluding the Russian River) enter the area; the larger of these - Salmon Creek and Scotty

Creek - have low gradients and barred estuarine mouths. All in all, there do not appear to be large, consistent additions of detritus from this particular stretch of coast.

As for losses of sand inland, the only extensive area not backed by 50 to 200 foot high cliffs occurs at Salmon Creek Beach, where a large area of what appears to be an old spit connecting Bodega Head to the mainland is now covered by both stabilized and active dunes. This area has been the site of loss of sand from the littoral zone for a long time but the rate of sand loss is not known exactly; however, an annual rate of loss has been estimated*. The main dune area revealed no ferruginously-cemented sands or pronounced buried soil profiles as were noted on the Point Reyes Peninsula and therefore it seems reasonable to conclude that the main build-up of dune sand behind Salmon Creek Beach is of rather recent origin.

In contrast to the large accumulations of sand at Salmon Creek Beach, the diorite mass which makes up Bodega Head is characterized primarily by erosional features such as wave-cut cliffs and benches, stacks, points, sea caves, and pocket coves. To a large degree the irregular nature of the coast line is related to differences in hardness and degree of fracturing and jointing of the diorite.

The diorite is veneered by terrace deposits which tend to grade upward from essentially dioritic material to material containing a large proportion

* Kadib, Abdel-Latif, Calculation Procedure for Sand Transport by Wind on National Beaches, Coastal Engin. Res. Center Misc. paper 2-64, April 1964.

of Franciscan-derived detritus. This terrace material could be the source of a large proportion of the sediment contributed to the littoral zone from Bodega Head; their presence could explain the occurrence of sands which are relatively high in "non-dioritic" minerals in a general area where the pocket beaches contain sands which are almost completely devoid of "non-dioritic" minerals. An alternate explanation would involve the mixing of the locally-derived dioritic sands with Franciscan-derived sands from upcoast in certain areas and the almost complete masking of these sands from the north by dioritic debris in other local areas along the Head (principally in the pocket coves).

A wave-cut bench occurs along a large portion of the coast line of Bodega Head. This bench varies in elevation; in some localities it coincides with present day sea level, in other localities it is found five or ten feet above sea level. In some instances terrace materials are preserved on this bench and this occurrence (especially when compared with similar occurrences on Tomales Point and the Point Reyes Peninsula) suggests very strongly that a great deal of the cliff erosion affecting Bodega Head took place during an earlier cycle of erosion and therefore that not as much diorite has been recently contributed to the littoral zone as might at first be supposed. At the same time, there is no evidence of large present day losses of sand from the littoral zone to Bodega Head.

Doran Beach, which forms the prominent spit just east of Bodega Head, appears to be neither gaining nor contributing much sand at the present.

The spit is composed of sands which have a heavy mineral composition just about evenly divided between dioritic and Franciscan-derived minerals. The spit is covered by low stabilized dunes which are occasionally breached by storm waves. Although Doran Beach owes its origin to sand lost from the littoral zone, there is no evidence concerning the rate of loss (except for the lack of any indicators of relatively great age, for the sands), such as buried soil horizons.

South of Doran Beach the coast is characterized by a stretch of rather high cliffs cut back into Franciscan rocks. This coastal area is highly irregular in detailed configuration and has a very rocky shore; a large number of the cliffs are associated with massive landslides, which apparently furnish a considerable amount of Franciscan debris to the sea. Where small slides occur, the cliffs are fronted by colluvial material which is stable and often covered by vegetation; in these areas the contribution of detritus to the littoral zone appears to be relatively small. The two large streams, Americano Creek and Stemple Creek, which flow to the coast in this area have very low gradients and long estuarine mouths which are periodically barred. The fact that these estuaries ("esteros") are open at various times, even during the summer months when stream flow is lowest and additions to the beaches are greatest, suggests that relatively little sand is moving along this part of the coast. Similarly, there is little loss of sand from the littoral zone except possibly back into the sand flats behind the bars at the mouths of the estuaries; these sand accumulations, like the bars themselves, appear to be rather ephemeral features.

The beach sands along this stretch of coast contain a mineral assemblage exhibiting a ratio of approximately 2:1 in favor of Franciscan-derived minerals. There is a suggestion of a decrease in dioritic content going south away from Doran Beach. The dioritic components of the sands might come from Bodega Head via Doran Beach or possibly from the erosion of the diorite body, which though presently submerged, connects Tomales Point and Bodega Head.

To the south the zone of high cliffs gives way to the lower areas backing Dillon Beach. Dillon Beach is an extensive area covered by both stabilized and active sand dunes and is quite similar to Salmon Creek Beach. No evidence was noted which suggests the existence of older dunes; therefore, Dillon Beach is considered to represent an area of relatively recent loss of sand to the mainland from the littoral zone.

Considering the evidence at hand, it is difficult to arrive at any single explanation for the nature of the province which extends along the coast from just south of Salmon Creek Beach to the mouth of Tomales Bay (Cherry's province 6). The mixing of dioritic and Franciscan-derived minerals could reflect the influence of littoral drift which is taking place at the present or which took place in the past. Present day local contributions of sand apparently are not large and therefore might not be sufficient to effectively "flood out" even relatively small amounts of sediment brought in by littoral drift.

West of Dillon Beach across the mouth of Tomales Bay is Tomales Point,

a dioritic body which forms a prominent peninsula whose western flank is exposed to the open ocean. The seaward margins of the point are characterized by wave-cut benches, steep cliffs, small promontories, stocks, and pocket coves. There is not a significantly large drainage system on this narrow peninsula. The presence of hanging valleys on the seaward side of the Point indicates that greater recent erosion has taken place here than on the Tomales Bay side.

Several large re-entrants occur along the steep, rocky coast, particularly at and near McClures Beach. These re-entrants are generally the sites of Quaternary deposits which have been deposited on an older, pre-existing wave-cut coast line. A basal conglomerate of dioritic material with a very small proportion of Franciscan-derived material can be found resting on older wave-cut benches and over and around small pre-existing headlands. These older wave-cut benches are present near, or slightly above, present day sea level. The basal dioritic conglomerates are capped by reddish brown, ferruginously-cemented sands which are high in Franciscan-derived minerals and which are interpreted as representing older beach and dune deposits; the higher deposits must certainly consist entirely of dune sands. These ferruginously-cemented deposits reach elevations of approximately 300 feet and attain a maximum thickness of something in excess of 200 feet (part of this thickness might be the result of later reworking and further piling-up of the old dune sands).

The beaches along Tomales Point generally reflect the rock types

immediately backing the shore; the deposits are predominantly dioritic where the diorite is present and are high in Franciscan-derived minerals where the older beach and dune deposits are exposed. Gullies in these older deposits aid in the bringing of Franciscan-derived sands to the littoral zone. The highly non-dioritic nature of these ferruginously-cemented sands indicates that they could not have been derived from the present offshore deposits since these offshore sands have a definite predominance of dioritic minerals. All the evidence points to these older deposits of sand as being associated with an earlier cycle of erosion and deposition.

Both the resistant nature of the diorite and the indications of considerable cliff recession during an earlier period of erosion suggest that the prominent dioritic cliffs are not related to a particularly rapid rate of present day erosion and, therefore, that the contribution of dioritic detritus is not large. The ferruginously-cemented sands have been eroded back to positions where they are generally protected by fairly wide beaches. No low areas are available for the loss of sand inland and any small dunes which occur at the base of cliffs are probably quite ephemeral.

South of the cliffed coast line of Tomales Point is an extremely long, linear beach, Point Reyes Beach. Both the shore line and coast line along this beach are oriented parallel to the wave fronts of the dominant swell; such an orientation creates conditions which are considered to work against the existence of any large scale unidirectional littoral drift. The beach is relatively wide (100 to 250 feet) and is backed by a number of different

rock types which exhibit varying mineralogic compositions and resistances to erosion.

The northernmost two miles of beach are backed by cliffs cut into the basal sands and shales of the Middle Miocene. The sands are derived from the diorite exposed along Tomales Point and Inverness Ridge, and therefore contain a predominance of dioritic minerals. The shales are typified by an abundance of zircon and garnet and by little else in the way of heavy minerals. South of this zone of exposed Middle Miocene strata the beach is backed by reddish brown; ferruginously-cemented sands which are high in Franciscan-derived minerals; these deposits are correlative with similar sands exposed on Tomales Point.

These reddish brown sands were deposited against and over essentially vertical cliffs cut into the Middle Miocene shales and often completely obscure these cliffs. A narrow wedge of indurated angular colluvial material derived from the cliff faces occurs at the contact between the buried cliff faces and the older dune sands. Although there is no progressive diminution in stratigraphic thickness of these older sands as they are traced northward along the beach, the width of these ferruginously-cemented deposits fronting the buried cliff faces does become progressively smaller through greater erosion at the north end of the beach. Finally at a point approximately one mile below the north end of the beach, these deposits of older sand disappear altogether, having been completely removed by the effects of long term wave attack. As a result of the removal of these older dune sands,

the pre-existing cliff faces in the Middle Miocene strata are once more exposed.

The Middle Miocene shales continued behind the remaining wedge of ferruginously-cemented sands southward for approximately a mile; south of this area, the Middle Miocene shales give way to the Upper Miocene siltstones and mudstones which cover most of the southwestern half of the Point Reyes Peninsula. These Upper Miocene beds are characterized by a relatively high content of dioritic minerals. Very locally, older terrace sands and gravels rich in Franciscan-derived detritus are preserved as cappings on some of the low hills (200 to 300 feet high) backing the southern half of Point Reyes Beach. At the very southernmost end of the beach, the older dune sands abut directly against the diorite and the steeply dipping, very resistant Paleocene conglomerates exposed at Point Reyes. The Paleocene conglomerates are highly indurated and contain a predominance of Franciscan-derived minerals.

The coast line along Point Reyes Beach is generally demarcated by cliffs cut into the semi-consolidated older dune sands or, at the northern end of the beach, into the Middle Miocene sandstones and shales. Although these cliffs are frequently overtopped and masked by recent sand dunes their existence can generally be detected by the height and linearity of the recent dunes. However, certain areas immediately behind the beach, particularly near the center of this section of coast, are quite low and if small cliffs or scarps in older sediments do exist, they must be very

low. Stabilized and active dunes form a more-or-less continuous blanket covering the greater portion of the area immediately behind the beach and often extend as far as one mile inland. In addition to the presence of the recent sand dunes, the exposed cliffs are typically fronted by accumulations of rill wash and other products of mass wasting which form miniature alluvial fans and fairly extensive apron-like features along the base of the cliffs. Most of these deposits show evidence of recent wave attack- (their seaward margins are typically nipped) and are probably rather ephemeral.

The more recent sand dunes are often separated from the older, ferruginously-cemented dune sands by a pronounced buried soil horizon and its associated iron pan. In some localities younger, less well-developed buried soil horizons also exist and are indicative of dune sands of intermediate age. At the southern end of the beach where the older dune sands reach elevations above 400 feet and thicknesses probably in excess of 200 feet, reworking of the older, underlying sands has taken place and the differentiation between older and younger (reworked) sands is very difficult.

The drainage area behind Point Reyes Beach is restricted to a narrow belt which seldom exceeds a mile in width. Only two significant drainages flow to the beach - the small stream near the north end of the beach and those which flow into the barred estuary forming Abbotts Lagoon. Many short canyons (usually less than one-half mile in length) have been cut back into the relatively softer sediments and sedimentary rocks backing the beach.

These canyons and the ephemeral streams flowing in them are characterized by the following features: (1) Low gradients over most of the stream course; knick points where most resistant beds (indurated soil horizons, etc.) are encountered, (2) Marshy and vegetation-choked courses, (3) Wide valleys in comparison to the width of the actual stream channels, (4) Only slight intrenching into valley fill, and (5) Canyon mouths obstructed by dunes, slump, and typically by large logs and other drift wood. All of this evidence points to rather limited contributions of sand via the streams in the area.

Obviously the area of Point Reyes Beach has been one of prolonged loss of sand inland from the littoral zone. The ages of the various dune sands involved in this process of loss of sediment from the littoral zone is not known but they could well extend back into the Pleistocene (10,000 to 12,000 years B.P.). The presence of buried soil horizons plus the varying degrees of stabilization exhibited by the dune sands suggest that the migration of sand from the littoral zone onto the areas behind the beach has been periodically interrupted; therefore, it is extremely difficult to estimate rates of sand loss. In any event, large quantities of sand have been lost inland from the littoral zone along Point Reyes Beach and the loss is continuing to take place, at least locally, at the present time.

As far as the transfer of sand to the littoral zone from the area of Point Reyes Beach is concerned, it is also difficult to estimate the volume of sand and the rate of movement involved. Present wave attack does periodically result in the local erosion of sand from the ferruginously-

cemented deposits backing the beach (extremely deep, cusp-like indentations back into the beach sands and into the cliffs behind the beach have been observed at widely spaced intervals along the beach). Very little transfer of sand out to the ocean appears to be associated with cliff erosion or stream action at present although the presence of deep, flat-floored gullies and relatively steep, high cliffs cut into the older dune sands clearly demonstrate that considerable removal of sand has taken place at some time in the past.

The sands on the beach and in the offshore areas along Point Reyes Beach (Cherry's province 4) contain mineral assemblages high in typical Franciscan-derived minerals, notably augite. Red chert and greenstone pebbles are also characteristic of these deposits and are typically derived from the Franciscan. Such sediments can come from neither the Middle Miocene nor the Upper Miocene strata. Since the sands found off Tomales Point at present are predominantly dioritic in composition and therefore notably low in augite, they can not be appealed to as the source for the augite-rich sands of Point Reyes Beach. Along the northern part of the beach, where the older dune sands are no longer preserved, there presently is no local source of Franciscan-derived minerals; but further south along Point Reyes Beach the older, ferruginously-cemented dune sands can, and apparently do, act as a source of sand. The large amount of material which must have been eroded from these older deposits in order to form the present day cliffs provides a logical source for much of the augite-rich

sand occurring in the beach and offshore zones at the present time.

It is important to note that although these Franciscan-derived older dune sands no longer exist along the northernmost part of Point Reyes Beach, they still appear to have a pronounced influence upon the mineralogic composition of the beach and shallow water sands in this particular area. Equally noteworthy is the presence of a large number of diorite pebbles along the northern end of Point Reyes Beach which suggests very strongly that some downcoast movement of dioritic material is currently taking place, but that the transfer of such material is not sufficiently great so as to result in the masking of the Franciscan-derived minerals already present in the beach and nearshore in this area.

If all of the older, ferruginously-cemented dune sands had been removed from the entire area backing Point Reyes Beach, rather than just from the northernmost section of beach, and only the cliffed Miocene strata were left exposed, the beach sands and nearshore deposits would still contain a predominance of Franciscan-derived minerals even though no local source for such sands would still be present. If such a situation were to develop at Point Reyes Beach in which the local source for contributions of Franciscan-derived sands to the beach and nearshore were completely eroded away, the remaining exposed local rock types would bear no relation to the current deposits on the beach and nearshore. Such conditions as outlined above add another complication to the interpretation of possible sources for sands occurring along the coast.

The question of the origin of the older, ferruginously-cemented dune sands exposed at Point Reyes Beach and along portions of Tomales Point bears directly on the investigation of littoral drift along the coast of Northern California. Both at Tomales Point and Point Reyes Beach, ferruginously-cemented sands of obvious Franciscan derivation occur deposited upon and essentially surrounded by rocks of non-Franciscan composition. There are only a limited number of possible sources for these Franciscan-derived sediments. The first of these is the higher, older terraces exposed on the southern half of Point Reyes Peninsula. There are no extensive remains of these higher terraces and therefore it is difficult to interpret their role as a possible source for the lower, relatively younger ferruginously-cemented sands. Aside from other considerations, the apparent paucity of augite and hypersthene, which would have resulted from intrastratal solution, would seem to rule out these higher deposits as a source for the lower sands, which are characterized by high augite and hypersthene content. Even if the older, higher terraces could be shown to be the principal source for the lower, ferruginously-cemented sands, the problem of explaining the presence of these older Franciscan-derived deposits themselves in an area of otherwise non-Franciscan rocks would still exist.

There seems to be no readily apparent process for either bringing Franciscan-derived material up along the coast from Franciscan exposures to the south or for bringing sediment in from the east across Tomales Bay

and over the dioritic rocks making up Inverness Ridge. Likewise it seems extreme to appeal to the relatively small exposures of Paleocene conglomerates at Point Reyes as the source of the augite-rich sands exposed along Point Reyes Beach and Tomales Point.⁴

In the absence of any information concerning the existence of Franciscan or Franciscan-like rocks offshore from the Point Reyes Peninsula, the one remaining possible explanation for the origin of the ferruginously-cemented dune sands involves the transport, by means of littoral drift during an earlier period, of material eroded from the Franciscan rocks north of the Point Reyes Peninsula. Drift of Franciscan-derived detritus during an earlier low stand of sea level would also provide an explanation for the presence of relatively coarse, garnet-rich deposits in deep water off Point Reyes Beach; such a low stand of sea level is also suggested by the thickness of fill in the larger streams and the characteristically underfit nature of the streams along the coast of California. Increased littoral drift during a lower stand of sea level might have been promoted by the absence of prominent barriers such as are presented by the present day headlands at Bodega Head, Tomales Point, and Point Reyes. Trask (1952) indicates that headlands in the general area north of Santa Barbara do not extend much beyond a depth of thirty feet; beyond this depth "the sandy floor of the ocean slope is encountered".

4. Dark porphyry pebbles and cobbles considered by Trask (1958) to be diagnostic of the Paleocene conglomerates on Point Reyes have been found along beaches which are obviously receiving debris directly from Franciscan rocks; these porphyries are therefore not diagnostic of any unique source.

A low stand of sea level would act in the direction of promoting stream erosion and contributions of detritus from this source while putting contributions from cliff erosion at a minimum. Such a situation would favor the creation of sands which would contain low ratios of dioritic to Franciscan-derived materials since most of the dioritic sands appear to result from cliff erosion and the majority of Franciscan-derived sands probably are associated with stream erosion and transport.

Based on the evidence at hand, it could be argued that most of the coast along the Point Reyes Peninsula was once fronted by Franciscan-derived sand brought in from the north by littoral drift during a low stand of sea level and that the present discontinuous pattern of Franciscan-derived deposits is the result of more recent masking and diluting by local contributions of dioritic debris. The present zones off Tomales Point and Point Reyes would therefore reflect areas of recent dioritic contributions while the deposits off Point Reyes Beach would represent an area of Franciscan-derived sands essentially free of masking and large scale dilution by dioritic minerals.

South of Point Reyes Beach is the bold, projecting mass of resistant diorities and Paleocene conglomerates which form Point Reyes; this is an area of distinctly dioritic sands. East of Point Reyes is Drakes Bay, an area containing primarily Franciscan-derived sands (Cherry's province 2). Drakes Bay is bordered by three principal rock types; the diorites of the eastern extension of Point Reyes; the rather soft siltstones, mudstones,

and silty sandstones of the Upper Miocene, which form the prominent cliffs along the northern and western coast of the bay; and the relatively resistant Middle Miocene shales along its eastern margins. Quarternary marine terrace gravels front about one mile of the easternmost exposures of the Upper Miocene beds and approximately three miles of the westernmost exposures of the Middle Miocene shales.

The dioritic rocks bordering the southwestern end of Drakes Bay are cut back slightly to form low cliffs which are fronted by a narrow, discontinuous shingle beach. This northeast facing margin of the east end of Point Reyes shows evidence of much less cliff erosion than does the exposed south-facing margin of the point. A large number of diorite pebbles and cobbles are scattered along many stretches of beach on the west side of Drakes Bay; relatively large concentrations of these cobbles are found in sheltered re-entrants along this part of the coast in association with cobble-sized concretions derived from the erosion of the Upper Miocene.

The Upper Miocene strata are predominantly siltstones and silty mudstones, which characteristically contain mineralogic assemblages which are quite high in dioritic minerals. The sandier phases of the Upper Miocene, which make up only a small fraction of the exposed thickness of the unit, are variable in mineralogic composition. Where the sands have been derived from the nearby diorities, they are naturally very high in dioritic minerals. Sands derived from other sources are typically low in dioritic minerals but are also low in Franciscan-derived minerals; these

sands are typically high in epidote (40-50%) and fairly high in zircon (10%). This distinctive mineralogic assemblage could be indicative of the solution of the less stable minerals (augite, hypersthene, etc.).

The Upper Miocene beds are characteristically cut back to form high (often 200 feet), steep cliffs. Although the cliffs show evidence of recent erosion, they are protected by fairly wide sandy beaches and locally by spits and sand dunes. Other lines of evidence will be introduced later which will also suggest that cliff erosion has not been taking place at a particularly high rate and that not a great deal of detritus is being contributed to the littoral zone from this source at the present time.

In contrast to the Upper Miocene strata, the Middle Miocene shales are rather resistant and form a rocky shore line with many small headlands and pocket coves. In the easternmost margin of Drakes Bay, these shales form high cliffs in an area characterized by massive landslides. Where these cliffs are subject to wave attack it is probable that considerable detritus is made available to the littoral zone. The shales are high in zircon and garnet and often contain considerable carbonate; with the possible exception of garnet, typical Franciscan-derived minerals are not abundant.

Very little sand can be expected to be moved to the littoral zone by the low gradient streams which periodically flow through the flat-floored valleys which characterize the drowned topography associated with a large portion of the area backing Drakes Bay. A number of the larger and more permanent streams in the area are barred by Limantour Spit or empty into the

broad estuaries ("esteros") formed behind this spit. Similarly, only a small amount of sand appears to be coming from the small, somewhat steeper streams which are flowing in narrow channels cut into valley fill in the area behind the eastern shore of Drakes Bay.

The Quaternary marine terrace gravels form steep, nearly vertical cliffs which are often 100 feet high. As the result of a large downwarp, which trends obliquely through the northern end of Drakes Bay, the terrace deposits become progressively lower toward the west and finally dip beneath the present day beach sands just east of Limantour Spit. These same deposits are elevated to the southeast where their basal zones are somewhere on the order of ten feet above sea level. These terrace gravels generally consist of poorly sorted angular fragments of Upper Miocene siltstones, mudstones, and sandstones and Middle Miocene shales. Very numerous sandy interbeds and lenses occur within the gravels. A prominent sand lens, which is high in zircon and garnet and contains a relatively high proportion of Franciscan-derived minerals, often is present at the base of the gravels. The gravels and associated sands generally yield material which is slightly more dioritic than Franciscan in mineralogic composition. The augite content of these sediments is low (one to two percent); zircon makes up about forty percent of the identified heavy minerals and the combination of zircon and garnet ranges around fifty percent and over.

The lack of good sorting and rounding and the absence of well-developed bedding suggests that these gravels were deposited in a somewhat sheltered

environment, probably at the base of cliffs which were protected by a spit or bar. The sandier interbeds might have been deposited during periodic incursions of storm waves beyond the supposed bar or spit. A very similar deposit is presently forming at the base of the cliffs cut into the Upper Miocene strata which are protected by Limantour Spit. Periodically Limantour Spit shifts its location and is also breached by storm waves; these changes could result in cliff erosion and also in the deposition of wave-borne sand.

Since all of the local rock types surrounding Drakes Bay are relatively low in Franciscan-derived minerals, particularly augite, the presence of sands which were derived from the Franciscan and which are high in augite rules out the possibility of large contributions from present day local sources. There is no evidence which suggests that augite-rich older beach or dune deposits similar to those at Tomales Point and Point Reyes Beach ever existed along Drakes Bay but such a possibility can not be completely ruled out (particularly since the area has recently undergone local submergence). Similarly, there is no real basis for supposing that the Franciscan detritus presently found along the beaches and offshore came from the erosion of the higher, older terrace deposits on the Point Reyes Peninsula. It is equally difficult to appeal to the transport of Franciscan detritus derived from sources located to the east of Inverness Ridge and the San Andreas Rift Zone or to the south along the coast below Bolinas Bay.

At the same time, most of the evidence argues against recent transport of Franciscan-derived sands from north of Point Reyes downcoast to Drakes

Bay. Even if large amounts of Franciscan-derived sand were presently able to move past Point Reyes Beach and around Point Reyes, they could not pass through the highly dioritic zone off Point Reyes, without (1) become greatly diluted with dioritic minerals or (2) greatly diluting the dioritic content and thereby changing the very nature of the mineralogic composition of that zone (Cherry's province 1).

However, a reasonable case, based upon currently available evidence, can be built which supports a theory involving the transport of Franciscan-derived sands into Drakes Bay during an earlier period, particularly at a low stand of sea level. Although such a theory rests mainly upon the ruling out of alternative explanations for the supplying of Franciscan-derived sands to Drakes Bay, it is congruent with the evidence found at Tomales Point and Point Reyes Beach.

A further basis for ruling out local sources of sediment is revealed by consideration of the coast and shore lines along and adjacent to Drakes Bay. The Upper Miocene rocks backing Drakes Bay are protected from much wave attack not only by relatively wide beaches but also by Limantour Spit and its associated "esteros". The presence of what is interpreted as a present-day wave cut bench in the Upper Miocene rocks along the western shore of the bay does indicate that something on the order of 50 to 100 feet of cliff recession probably has taken place during the current cycle of erosion. Although contribution of sediment from the cliffs does take place, there are also indications of sizeable losses of sand from the

littoral zone to the shore areas. Limantour Spit is an obvious area of gain of sand from the littoral zone; many dunes (active and stable) occur on the spit and along many stretches of beach (particularly just east of Limantour Spit). An extensive sand flat just in back of the mouth of Drakes Estero indicates that sand can be trapped behind the spit, probably during periods of storm waves coming from the south (the existence of mud flats at the heads of the "esteros" tends to rule out derivation of this sand from inland sources). Also the location and configuration of the pre-existing coast line along which the Quaternary marine terrace gravels were deposited line up quite closely with that of the present and thereby indicate that little significant change has taken place since the older coast line was cut.

In contrast to these areas of negligible supply of sediment to the littoral zone, in the areas immediately adjacent to Drakes Bay, both to the east and west, a different set of conditions exists - conditions which suggest a large contribution of sediment to the littoral zone. Along the southern margin of Point Reyes, the high, steep cliffs give evidence of considerable erosion (especially when compared with the low cliffs found along the sheltered northeastern side of the point). The occurrence of extremely dioritic sands off Point Reyes (Cherry's province 1) also points to the fact that significant cliff erosion has recently taken place and that relatively large quantities of recent detritus have been derived from this area. Likewise, the tongue of dioritic sand which protrudes northward

around the eastern end of Point Reyes and up into Drakes Bay can logically be fitted into a situation in which younger sediments (dioritic material from Point Reyes) are presently overrunning the pre-existing deposits (Franciscan-derived sands presumably transported into the area during an earlier period).

Similarly, at the southeastern margins of Drakes Bay, the rocky, irregular nature of the shore line, the steep, high cliffs, and the massive landslides all combine to indicate relatively large additions of detritus related to the recent erosion of the Middle Miocene shales. Any large volume of sand derived from this detritus would mask or dilute pre-existing sands in the area and would give rise to a new mineralogic assemblage (an assemblage which would reflect the mineralogic composition of the Middle Miocene shales); the assemblages high in carbonate, zircon, and garnet found along the southeastern end of Drakes Bay (Cherry's province 3) can best be explained by such a set of conditions. In this area, the pre-existing Franciscan-derived sands, which are characterized by a high percentage of augite, apparently have been overwhelmed by a new assemblage of minerals associated with the recently eroded and deposited sediments derived from the shales.

V. General Conclusions

The three previously proposed explanations for the existence of distinct mineralogic provinces in the area under investigation can now be considered in the light of the evidence and inferences presented above. Of the three explanations, the third appears to be in closest harmony with actual conditions as they have been observed. That is to say, the occurrence of Franciscan-derived sands along Point Reyes Beach, parts of Tomales Point, and along the major portion of Drakes Bay can best be explained by appealing to the existence of sands which were associated with an earlier period (or periods) of erosion, downcoast transport, and deposition and which have persisted to the present day, in certain areas, in largely unmodified states.

If the present distribution of heavy minerals along this part of the coast does in part reflect the occurrence of older sands which have survived to the present time as distinct mineralogic assemblages, then their existence should be congruent with a logical sequence of events which has affected the erosion, transportation, and deposition of sand in the area. The following, therefore, is a brief summary of the evidence of past events which might explain how these older deposits came to be located in their present situations and how they have been able to persist without the loss, through later masking or diluting by more recent detritus, of their original characteristics.

Because of the lack of sufficient field data and the complications imposed by the complex structural history of the general area, no attempt

is made at correlating the following sequence of events with other quaternary glacio-eustatic sequences. Similarly, no attempt is made at a correlation of the events which took place on opposite sides of the San Andreas Fault Zone.

Starting with the deposition of the higher terrace sands and gravels found on the southwestern portion of the Point Reyes Peninsula, the proposed sequence of events is as follows:

(1) A period of high relative sea level (presumably during the Middle or Late Pleistocene) is indicated by the presence of the Franciscan-derived marine terrace deposits which occur in an area apparently otherwise devoid of pre-existing Franciscan or Franciscan-like rocks (with the exception of the very limited exposures of Paleocene conglomerate, which contain Franciscan-derived minerals). The existence of downcoast movement, possibly when the main dioritic bodies were submerged, is strongly suggested for this period.

(2) A period of a lower relative sea level (on the order of 100 to 200 feet) followed by a still stand or slight rise in sea level is suggested by the presence of the very flat areas immediately behind the buried and partially exhumed cliffs behind Point Reyes Beach. This might have also been the period when the thick marine terrace gravels were deposited along the eastern side of Drakes Bay.⁵

5. It is quite possible that periods "2" and "3" are actually coincident and only appear to be separate because of later structural complications.

(3) A succeeding period of slight lowering of relative sea level followed by a still stand or slight rise in sea level would explain the occurrence of the wave-cut benches and associated sea cliffs along Tomales Point, Point Reyes Beach, and Bodega Head. The basal conglomerates and related beach sands would also have been deposited during this period. Similar features might have been formed along Drakes Bay at this same time. This also appears to have been a period when a large portion of the present day coastal configuration was initially sculptured.

(4) A pronounced lowering of relative sea level (probably on the order of 200 feet and related to the last large glacial lowering of sea level) is proposed as the next period in this sequence. 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 dioritic headlands and into a zone which might have been conducive to large-scale downcoast transfer of sediment. Large contributions of Franciscan-derived detritus would have resulted from the renewed activity of the mainland streams; at the same time, cliff erosion (the main source of dioritic debris) would be at a minimum. The coarser zones which definitely occur off Point Reyes Beach would also be explained by a significant lowering of sea level. Above all, the creation of large areas of exposed beach sands would provide a source for the older, ferruginously-cemented dune sands which were deposited up against and over the pre-existing cliffs at Point Reyes Beach and Tomales Point (and possibly also at Bodega Head).

(5) A rise in relative sea level took place in the next and last period and brought sea level to its present stand (a stand which might roughly coincide with that which was in force during the third period of this proposed sequence). The rise in sea level would simultaneously decrease the amount of sand contributed from the Franciscan, by limiting stream erosion, and increase the addition of dioritic material, by extending cliff erosion. In areas which are backed by relatively softer strata (including most of the areas behind Point Reyes Beach and Drakes Bay), cliff erosion during this present period has not been great because the sea has not advanced very far beyond the zone previously eroded during earlier periods (principally during period 3).

This last point deserves re-emphasis since it demonstrates, in part, why the relatively resistant dioritic headlands are presently furnishing significantly large amounts of detritus while the other less resistant rocks apparently are adding relatively little material. The broad wave-cut benches and their associated conglomerates indicate that intensive wave attack took place along the coast during an earlier period of erosion. Although the diorites were eroded considerably, the softer rocks (Middle and Upper Miocene strata) must have been eroded even more. Such differential erosion must have worn these softer sedimentary rocks back to positions behind those occupied by the exposures of dioritic rocks. Following a period of lower relative sea level, the recent re-advancing sea would not only encounter the dioritic rocks before reaching the cliffed sedimentary

rocks but the protruding diorites would also be subjected to greater concentrations of wave attack. The previous intervening period of lower sea level exposed the diorites to extensive weathering and thereby further aided in the later erosion of these otherwise relatively resistant rocks. The extensive occurrence of only slightly indurated older sediments (mainly the marine terrace gravels and the ferruginously-cemented dune sands) in front of much of the Miocene strata provides a further indication of the fact that wave attack associated with the present stand of sea level has not been particularly effective in these areas of pre-existing cliffs.

VI. Summary

A previous study of beach and nearshore deposits along a portion of the coast of Northern California indicates that sands containing distinctly different assemblages of heavy minerals often exist immediately adjacent to one another. Specifically, areas of sand characterized by detritus derived from the Franciscan Formation are found along the coast interspersed with areas containing a predominance of sands derived from dioritic rocks. Moreover, many of the Franciscan-derived sands occur in areas which are essentially devoid of any present day sources for such deposits and which often present only exposures of rocks high in dioritic minerals.

The existence of these distinctly different assemblages of heavy minerals along the coast rules out any significant present day coastwise littoral transport of sand, particularly from a single major source such as the Russian River. Neither present day littoral transport of Franciscan-derived material nor the supply of such sands from local sources can be appealed to in order to account for the existing deposits of Franciscan-derived sands along many sections of the coast. The occurrence of these sands appears to be related to the transport of sediment during an earlier period of littoral drift. The present discontinuous distribution of these older sands is related to the effects of local masking and dilution resulting from the deposition of detritus supplied by the recent erosion of non-Franciscan rocks (principally dioritic rocks.)

The earlier migration of Franciscan-derived sands is believed to have

taken place during a low stand of sea level. A low stand of sea level would have resulted in the following: (1) The increase in contribution of detritus from the Franciscan through the rejuvenation of stream erosion, (2) The decrease in contribution of non-Franciscan material as a result of decreased cliff erosion, (3) The promotion of downcoast transport of sediment by the shifting of the littoral zone out away from the obstructions presented by the dioritic headlands, and (4) The creation of a source for the extensive older dune sands by exposing wide areas of beach sands.

Present day erosion and contributions of sediment to the littoral zone are relatively limited and, as a result, the Franciscan-derived sands associated with the earlier littoral drift are masked only in certain areas. The lack of recent erosion is related to the fact that much of the current coast line was cut at an earlier period and that the sea has only locally advanced beyond the zone of earlier erosion. The occurrence of this earlier period of erosion is clearly demonstrated by the existence of wave-cut benches and cliffs currently being exhumed from beneath old beach and dune deposits.

The existence, within present day nearshore and beach deposits, of areas of sand which are related to earlier cycles of erosion, coastwise transport, and deposition of sediment along a portion of the coast of Northern California points to the possibility of similar occurrences in other areas. Such possibilities should be taken into consideration in the investigation of recent littoral drift, not only those directly related to

the study of heavy mineral distributions but also those concerned with the distribution of natural occurring radioactive substances. Similarly, studies of the recent transfer of sand to and from the littoral zone should take into account the effects produced by previous periods of coastal erosion and littoral transport.

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APPENDIX A

Tables 1-6: Heavy mineral composition for all samples analyzed (61-250 microns).

Note: Figures in the first fifteen columns represent percentages of identifiable translucent (non-opaque) mineral grains excluding biotite and chlorite. The minerals are arranged in the following groups:

1. "Dioritic" Minerals - Apatite, sphene, and "dioritic" hornblende.
2. "Non-dioritic" Minerals - "Metamorphic" hornblende, augite, glaucophane, actinolite-tremolite, garnet, hypersthene, carbonate, and lawsonite.
3. "Others" - Zircon, Epidote, and "others" (includes non-diagnostic minerals of infrequent occurrence).

The figures under the heading "Biotite" represent the total grains of biotite counted and are not included in the calculation of percentages of identifiable heavy minerals.

The figures under the heading "Total Unidentified + Biotite + Chlorite" represent the total number of opaque, highly altered, and otherwise unidentifiable grains counted plus total grains of biotite and chlorite counted.

The figures under the heading "Dioritic/Non-dioritic" represent ratios of the percentage of "dioritic" grains to the percentage of "non-dioritic"

grains; values are given to the nearest tenth. Values greater than 1.0 indicate predominantly "dioritic" sands. Values less than 1.0 indicate predominantly "non-dioritic" sands.

Table 7: Comparison of median grain size for upper Miocene siltstones and recent sands.

Table 1. Russian River to Salmon Creek

Sample	Apatite	Sphene	Dioritic Hornblende	Total Hornblende	Metamorphic Hornblende	Augite	Glaucophanes	Actinolite + Tremolite	Garnet	Hyperssthene	Carbonate	Lawsonite	Zircon	Epidote	Others	Biotite	Total Unidentified + Biotite + Chlorite	Dioritic/Non-dioritic
A. 1	-	4	-	4	4	14	14	6	4	-	6	12	6	15	18	16	1724	0.1
5	1	-	-	-	-	7	78	2	-	-	1	1	-	-	10	1	387	0.0
8	-	1	1	2	1	8	3	1	7	-	55	1	4	10	8	58	1224	0.0
11	-	5	2	6	4	11	21	34	3	-	-	11	-	7	5	3	374	0.1
B. 3	-	5	1	4	3	20	11	12	12	5	-	7	5	12	13	2	745	0.1
4	-	3	1	2	1	3	20	15	4	1	-	4	1	7	33	1	2167	0.1
C. 7	4	5	3	4	1	28	3	10	4	-	1	4	5	24	8	14	1552	0.2
9	1	8	1	7	6	7	8	15	14	-	1	5	3	18	14	12	1577	0.2
12	1	2	-	2	2	4*	2	-	11	2	68	1	2	2	3	97	1006	0.0
D. 2	1	2	1	8	7	2	15	15	1	1	-	9	10	22	14	3	621	0.0
6	-	6	4	12	8	7	9	13	19	7	-	6	9	7	4	20	820	0.2
10	-	2	2	8	6	2	19	12	6	2	-	6	6	12	25	-	538	0.1

- A. Composite rock samples from Franciscan Formation exposed in cliffs.
 B. Colluvial and/or dune deposits fronting Franciscan cliffs.
 C. Stream deposits in areas of exposed Franciscan and Merced Formations.
 D. Elevated, ferruginously-cemented marine terrace deposits.

* Identification uncertain.

Table 2. Bodega Bay and Bodega Head

Sample	Apatite	Sphene	Dioritic Hornblende	Total Hornblende	Metamorphic Hornblende	Augite	Glaucophane	Actinolite + Tremolite	Garnet	Hyperssthene	Carbonate	Lawsonite	Zircon	Epidote	Others	Biomite	Total Unidentified + Biomite + Chlorite	Dioritic/Non-dioritic
A. 13	-	1	2	6	4	10	7	34	9	2	-	3	14	9	5	7	1020	0.0
B. 14	1	2	14	23	9	16	17	23	4	3	-	4	1	1	6	1	292	0.2
15	-	3	30	36	6	8	15	23	4	-	-	3	-	6	2	2	422	0.6
C. 16	2	5	71	71	-	4	2	6	1	3	-	1	2	5	-	58	530	4.6

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- A. Older, ferruginously-cemented marine terrace deposits on mainland.
 B. Older, ferruginously-cemented marine terrace deposits on Bodega Head.
 C. Older, ferruginously-cemented dune sands on Bodega Head.

Table 3. Tomales Point

Sample	Apatite	Sphene	Dioritic Hornblende	Total Hornblende	Metamorphic Hornblende	Augite	Glaucophane	Actinolite + Tremolite	Garnet	Hyperssthene	Carbonate	Lawsonite	Zircon	Epidote	Others	Biotite	Total Unidentified + Biotite + Chlorite	Dioritic/Non-dioritic
A. 17	-	21	59	60	1	9	-	1	1	-	-	2	2	3	2	18	.26	6.2
B. 18	-	29	5	7	2	14	3	4	13	2	-	-	6	16	7	15	629	0.9
24	1	5	88	88	-	-	1	3	-	-	-	-	2	1	-	403	440	23.5
C. 20	2	23	8	10	2	11	4	7	24	3	-	4	-	4	1	54	711	0.6
21	-	21	3	4	1	5	2	1	34	2	-	1	26	3	1	1	713	0.5
D. 19	1	6	-	4	4	23	3	18	17	4	-	3	8	8	5	4	648	0.1
22	-	5	7	9	2	18	6	10	19	3	-	3	7	9	11	2	664	0.2
E. 23	-	12	8	9	1	16	4	5	13	3	-	3	24	7	4	10	469	0.4

A. Sands from beach backed by diorite cliffs.

B. Basal diorite material in older marine terrace (Note: 18 includes lowermost older dune sands).

C. Sands from beaches backed by older, ferruginously-cemented dune sands.

D. Older, ferruginously-cemented dune sands.

E. Stream deposit in area of exposed older, ferruginously-cemented dune sands.

Table 4. Point Reyes Beach and Southwestern Point Reyes Peninsula

Sample	Apatite	Sphene	Dioritic Hornblende	Total Hornblende	Metamorphic Hornblende	Augite	Glaucophane	Actinolite + Tremolite	Garnet	Hyperssthene	Carbonate	Lawsonite	Zircon	Epidote	Others	Biotite	Total Unidentified + Biotite + Chlorite	Dioritic/Non-dioritic
A. 29	-	13	5	10	5	16	2	4	23	2	-	8	3	5	14	14	864	0.3
30	-	1	-	2	2	30	5	14	14	6	-	7	8	8	5	1	620	0.0
B. 26	-	9	8	27	19	5	15	5	7	9	-	7	8	5	3	-	312	0.5
27	-	5	6	12	6	14	6	9	11	8	-	2	20	9	4	2	493	0.2
33	-	3	2	6	4	5	15	8	5	5	-	17	3	18	15	1	515	0.1
34	1	7	8	10	2	13	12	8	11	-	-	8	20	1	4	2	1043	0.3
39	-	6	2	10	8	6	18	11	9	9	-	11	6	9	4	9	775	0.1
40	-	2	4	8	4	23	8	9	19	4	-	4	10	9	5	1	432	0.1
41	-	4	1	6	5	23	1	2	23	18	-	7	4	8	4	1	693	0.1
42	-	5	6	9	3	27	4	8	11	3	-	7	9	10	7	1	713	0.2
43	-	6	2	4	2	11	5	7	30	2	-	3	20	7	5	-	505	0.1

A. Recent dune sands and associated soils.

B. Older, ferruginously-cemented dune sands (including associated buried soil horizons).

Table 4 (Con't). Point Reyes Beach and Southwestern Point Reyes Peninsula

Sample	Apatite	Sphene	Dioritic Hornblende	Total Hornblende	Metamorphic Hornblende	Augite	Glaucophane	Actinolite + Tremolite	Garnet	Hyperssthene	Carbonate	Lawsonite	Zircon	Epidote	Others	Biomite	Total Unidentified + Biomite + Chlorite	Dioritic/Non-dioritic
C. 32	-	7	13	17	4	8	14	9	7	5	-	3	6	14	10	2	380	0.3
36	-	5	1	5	4	13	10	8	12	7	-	13	11	9	7	-	x	0.1
37	-	1	2	2	-	2*	34	20	1	-	-	13	9	11	6	10	247	0.0
38	-	1	1	2	1	3*	32	12	2	-	-	24	6	17	2	15	392	0.0
D. 28**	16	11	11	11	-	6*	-	6*	38	-	-	-	12	6*	6	26	142	0.5
31**	17	8	8	8	-	2*	-	-	15	2	2	-	33	-	-	9	729	2.4
E. 25	-	3	5	5	-	-	1	-	40	-	-	-	50	1	-	122	212	0.2
F. 35	11	22	45	45	-	1	-	-	2	-	-	1	14	6	-	13	383	20.0

C. Higher, older marine deposits (Note: 32 and 36 might represent younger deposits).

D. Middle Miocene Shales.

E. Middle Miocene Sandstone.

F. Upper Miocene Siltstone.

* Identification uncertain.

** Less than 100 identifiable grains counted (Indicative of low heavy mineral content).

x Not recorded.

Table 5. Point Reyes

Sample	Apatite	Sphene	Dioritic Hornblende	Total Hornblende	Metamorphic Hornblende	Augite	Glaucophanite	Actinolite + Tremolite	Garnet	Hyperssthene	Carbonate	Lawsonite	Zircon	Epidote	Others	Biotite	Total Unidentified + Biotite + Chlorite	Dioritic/Non-dioritic
A. 44**	0	1	24	25	1	9	6	2	15	-	1	1	36	4	0	22	893	
45	-	4	21	21	-	10	2	3	4	-	1	1	51	2	1	5	134	
47	30	8	2	2	-	-	-	2	26	-	-	-	27	3	5	214	539	1.4
B. 46	-	5	24	26	2	19	2	3	13	2	2	1	18	4	5	6	271	1.4
C. 48	7	25	14	15	1	3	3	3	15	2	-	4	6	10	7	20	365	1.5

- A. Paleocene conglomerate and associated residual soils.
 B. Reworked older dune sands.
 C. Upper Miocene Siltstone unconformably overlying Paleocene conglomerate.
 ** Less than 100 identifiable grains counted (Indicative of low heavy mineral content).

Table 6. Drakes Bay

Sample	Apatite	Sphene	Dioritic Hornblende	Total Hornblende	Metamorphic Hornblende	Augite	Glaucophane	Actinolite + Tremolite	Garnet	Hyperssthene	Carbonate	Lawsonite	Zircon	Epidote	Others	Biotite	Total Unidentified + Biotite + Chlorite	Dioritic/Non-dioritic
A. 66	-	7	14	21	7	18	8	3	6	8	-	10	2	8	9	40	781	0.4
B. 58	1	8	23	25	2	19	13	6	3	3	-	12	2	5	3	7	1084	0.6
C. 50	6	8	68	68	-	-	1	1	2	-	-	-	7	6	-	15	185	20.5
51	4	5	78	78	-	-	-	1	3	-	-	1	3	5	1	2	78	21.8
52	6	7	60	60	-	1	-	-	6	-	-	-	3	17	-	2	77	10.4
53	8	30	22	23	1	2	-	2	11	-	-	-	11	13	-	6	212	3.5
57	2	10	53	53	-	-	-	-	3	-	-	-	5	24	1	-	54	13.0
60	1	9	58	58	-	-	3	4	-	-	-	-	1	21	3	3	94	9.6
D. 49	2	27	38	38	-	1	2	2	12	-	-	1	6	5	4	78	185	3.7
54	2	13	52	57	5	2	4	4	6	-	-	-	1	10	-	2	387	3.2
55	-	5	1	2	1	1*	5	9	6	-	1	2	10	51	8	-	357	0.2
56	-	2	-	-	-	4*	9	6	4	-	-	4	9	41	21	-	256	0.1
59	-	9	38	40	2	2*	10	17	3	2	-	8	1	6	2	4	396	1.1
61	1	4	65	67	2	1*	-	8	5	-	-	-	2	10	2	6	193	4.4
73	-	1	-	-	-	-	-	-	1	-	96	1	1	-	-	7	773	0.0

A. Sand from berm

B. Sand from extensive sand flat behind mouth of Drakes Estero

C. Upper Miocene Siltstone (Note: 50-53 represents approx. 200 ft. section; 50 is top).

D. Upper Miocene Sandstone (Note: 73 represents basal conglomerate composed mainly of underlying Middle Miocene sediments).

* Identification uncertain

Table 6 (Con't) Drakes Bay

Sample	Apatite	Sphene	Dioritic Hornblende	Total Hornblende	Metamorphic Hornblende	Augite	Glaucophanes	Actinolite + Tremolite	Garnet	Hyperssthene	Carbonate	Lawsonite	Zircon	Epidote	Others	Biotite	Total Unidentified + Biotite + Chlorite	Dioritic/Non-dioritic
E. 64	-	4	37	37	-	1	4	2	10	1	-	1	19	17	4	-	206	2.2
65	-	5	27	28	1	-	7	6	9	-	-	9	14	11	12	4	287	1.0
67	-	16	13	13	1	2	1	3	12	-	-	4	33	13	5	-	334	1.2
68	-	16	9	9	2	4	2	2	18	-	-	-	38	6	5	86	922	0.8
69	-	14	18	18	1	2	2	2	13	-	-	1	33	11	4	6	461	1.5
71	7	14	6	6	1	6	4	1	11	2	1	-	46	2	3	12	652	1.0
72	-	6	5	5	1	11	3	5	22	5	-	4	29	9	1	-	487	0.2
F. 62	9	4	65	65	-	-	-	-	12	-	-	-	8	2	-	248	517	6.5
63	-	12	43	43	-	-	-	1	19	-	-	-	19	6	-	48	499	3.7
G. 70	6	3	6	6	-	1	1	2	5	1	53	1	18	2	1	27	546	0.2
74	2	19	14	14	-	-	1	1	7	1	-	-	46	7	4	6	612	3.2
75	4	10	8	8	-	2	2	3	12	-	22	3	24	6	3	2	525	0.5
76**	6	13	12	12	3	9	3	3	21	-	1	-	26	5	1	16	2093	0.7

E. Marine terrace gravels (Note: 72 represents basal sand lens in terrace gravels).

F. Stream deposits in areas of exposed diorite and Upper Miocene strata.

G. Stream deposits in areas of exposed Middle Miocene strata.

* Identification uncertain

** Less than 100 identifiable grains counted (Indicative of low heavy mineral content).

Table 7. Comparison of Median Grain Size for Upper Miocene Siltstones and Recent Sands

Location	Sediment	Sample	Median Diameter (microns)
Point Reyes Beach	Upper Miocene Siltstone	35	85*
Drakes Bay	"	50	75*
"	"	51	75*
"	"	52	75*
"	"	53	70*
"	"	60	85*
"	"	Average	<80*
Point Reyes Beach (Cherry's province 4)	Recent Beach and offshore sands	Average	> 200
Drakes Bay (Cherry's province 2)	Recent Beach and offshore sands	Average	> 200

*Median grain size of sand fraction (61-250 microns) obtained from the disaggregation of Upper Miocene siltstone. Siltstones typically contain less than 30% sand-sized material and considerably less than 1% material greater than 250 microns in diameter.

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