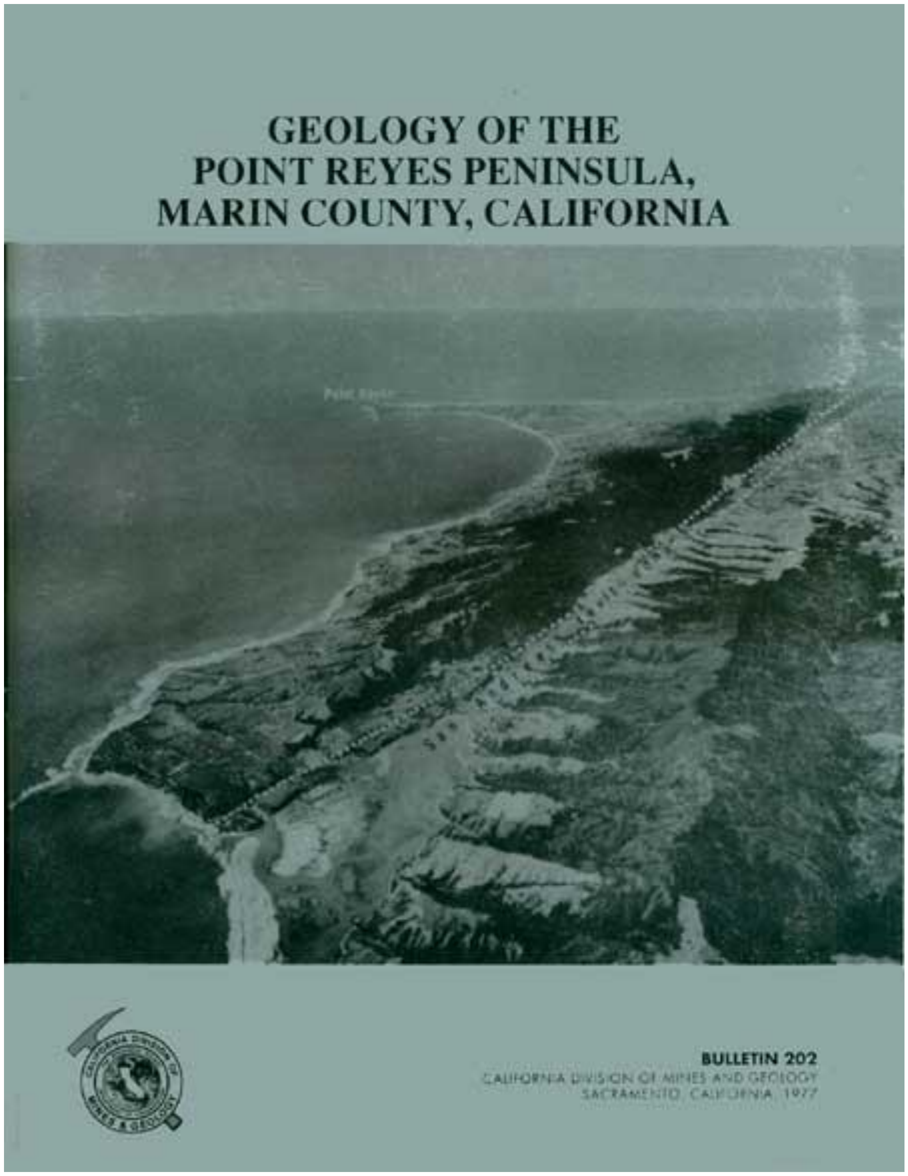
GEOLOGY OF THE POINT REYES PENINSULA, MARIN COUNTY, CALIFORNIA

By
Alan J. Galloway



California Division of Mines and Geology

Bulletin 202
1416 Ninth Street, Room 1341
Sacramento, California

1977

TABLE OF CONTENTS

CONTENTS

COVER

Front Cover: Aerial view of western Marin County and Point Reyes.

ABSTRACT

INTRODUCTION

Geologic Story
Location and Extent of Area
Field Investigation and Mapping
Previous Geologic Work
Acknowledgments

GEOGRAPHY

Topography
Drainage
Climate
Vegetation

DESCRIPTIVE GEOLOGY

Metamorphic Rocks
- Areal Distribution
- Lithology
  - Schist
  - Limestone
- Stratigraphy

Granitic Rocks
- Areal Distribution
- Lithology
- Stratigraphy

Franciscan Rocks
- Areal Distribution
- Lithology
  - Tectonic Inclusions
- Stratigraphy

Tertiary Rocks
- Paleocene
  - Point Reyes Conglomerate
    - Areal Distribution
    - Lithology

    - Stratigraphy
  - Miocene
    - Laird Sandstone
      - Areal Distribution
      - Lithology
      - Stratigraphy
    - Monterey Shale
      - Areal Distribution
      - Lithology
      - Stratigraphy
    - Other Miocene Rock Types
      - Clastic Dikes
      - Phosphatic Shales
      - Extrusive Igneous Rocks
  - Pliocene
    - Drakes Bay Formation
      - Areal Distribution
      - Lithology
      - Stratigraphy
    - Merced Formation
      - Areal Distribution
      - Lithology
      - Stratigraphy
- Quaternary Rocks
  - Pleistocene
    - Millerton Formation
      - Areal Distribution
      - Lithology
      - Stratigraphy
    - Olema Creek Formation
      - Areal Distribution
      - Lithology
      - Stratigraphy
    - Terrace Deposits
      - Marine Terraces
      - Stream Terraces
    - Boulders at Clam Patch
    - Older Beach Deposits
    - Sand Dunes

STRUCTURE

- San Andreas Fault
  - Width and Length
  - Associated Faults and Fracture Traces
  - Direction of the Movement
  - Shutterridges
  - Earthquakes and Creep
  - Stream Diversion
- Regional Structure
- Local Structure

Folds
Faults

GEOMORPHOLOGY

Fault Zone
Older Topography
Marine Erosion
Bolinas Lagoon and Tomales Bay
Alluviated Valleys
Point Reyes Promontory
Landslides

GEOPHYSICAL SURVEYS

GEOLOGICAL HISTORY

PreCretaceous through Pleistocene

ECONOMIC GEOLOGY

Coal and Peat
Gold
Greensand
Limestone
Petroleum
Scheelite
Stone
Water Supply

A NOTE ON THE GEOLOGIC MAP

SUGGESTIONS FOR FUTURE RESEARCH

REFERENCES CITED

State of California	The Resources Agency	Department of Conservation	Division of Mines and Geology
Edmund G. Brown, Jr.	Huey D. Johnson	Priscilla C. Grew	Thomas E. Gay, Jr.
Governor	*Secretary for Resources*	*Director*	*State Geologist*

ILLUSTRATIONS

Plate

1. Geologic map of Point Reyes Peninsula *(omitted from the online edition)*

Figures

1. Index map and generalized geologic map
2. Graph of mean daily atmospheric temperature
3. Type section of the Drakes Bay Formation
4. Variations of sea level during Ice Age
5. Diagrammatic sequential cross sections illustrating general geologic history of study area
6. Precipitation map

Tables

1. Mean daily atmospheric temperature
2. Surface water temperature
3. Mean monthly precipitation
4. Species of diatoms, Drakes Bay Formation
5. Species of diatoms, Drakes Bay Formation
6. Fossils from the Merced Formation
7. Fossil fauna of the Millerton Formation
8. Fossil flora of the Millerton Formation
9. Fresh water species of diatoms, Olema Creek Formation
10. Horizontal surface displacement, April 18, 1906
11. Analyses of limestone
12. Exploratory wells drilled to April 1, 1970
13. Low-flow characteristics of streams on Peninsula
14. Point Reyes Peninsula ranches and localities

Photographs

1. Aerial view of western Marin County and Point Reyes
2. Aerial view north toward Point Reyes
3. Metamorphic rocks in sea cliff near Kehoe Ranch
4. Point Reyes Conglomerate near Lighthouse
5. Laird Sandstone outcrop near Laird's Landing
6. Craggy Monterey chert outcrop near U—Ranch
7. Contorted Miocene cherts at Y—Ranch
8. Contorted Miocene cherts on Laguna Ranch
9. Duxbury reef
10. Impression of *Pinnixa galliheri* Rathburn
11. Bituminous sandstone dike in Monterey cherts
12. Basal sand of Drakes Bay Formation
13. Basal Pliocene glauconitic sand on Monterey chert
14. Diatoms from Drakes Bay Formation
15. Diatoms from Drakes Bay Formation
16. Merced Formation exposed in sea cliff
17. Olema Creek Formation
18. Olema Creek Formation
19. Diatoms from Olema Creek Formation
20. Bolinas—Drakes Bay terrace at mouth of Bear Valley
21. Aerial view of terraced surface
22. Older alluvial deposits exposed in road cut
23. Clam Patch

24. Older beach deposits
25. Older beach deposits on granitic surface
26. Mendoza syncline
27. Reverse fault in sea cliff
28. View south toward Drakes Bay and Limantour Spit
29. Landslides at Double Point
30. Miocene—Pliocene unconformity near U—Ranch

ABSTRACT

The Point Reyes Peninsula is a triangle of land about 100 square miles in area in western Marin County, California, bounded on the east by the valley of the San Andreas fault zone and on the remaining sides by the Pacific Ocean. This report describes the geology of the land west of the San Andreas fault zone on this peninsula. The principal topographic features are the linear depressions of the Olema Valley, Bolinas Lagoon, Tomales Boy, the high land of Inverness Ridge immediately west of these depressions, and the promontory of Point Reyes.

The oldest rocks of the area are the metamorphosed limestones and schists which occur as roof pendants in the granitic rocks of Inverness Ridge. Overlying the granitic rocks at Point Reyes is the Paleocene Point Reyes Conglomerate. At Inverness Ridge the granitic rocks are overlain by Miocene Monterey Shale of Relizian to Mohnian age. The Pliocene Drakes Bay Formation lies between Point Reyes and Inverness Ridge. These beds lie unconformably on the Monterey Shale and overlap onto the granitic basement at Point Reyes. The Pliocene Merced Formation, close to Bolinas, is very similar to that of the type section of the Merced Formation 20 miles to the southeast. These beds lie on rocks of the Franciscan Formation which are involved in the fault zone. The Pleistocene (?) Olema Creek Formation lies on rocks of the Franciscan Formation in the fault zone near Olema. Pleistocene non-marine terrace deposits overlie wove-cut platforms of Miocene rocks in several places. Old beach deposits of Pleistocene age are found at McClure's Beach on the west side of Tomales Point and along Point Reyes Beach. A very large area of ancient landsliding is found near Double Point.

Pleistocene non-marine terrace deposits overlie wave-cut platforms of Miocene rocks in several places. Old beach deposits of Pleistocene age are found at McClure's Beach on the west side of Tomales Point and along Point Reyes Beach. A very large area of ancient landsliding is found near Double Point.

The structure of the area is dominated by the San Andreas fault zone which is about a mile and a half wide and traverses the Franciscan, Miocene, and granitic rocks. The surface rupture of the 1906 San Francisco earthquake lies toward the center of the fault zone at the south end of the Olema Valley, but lies closer to the west side of the fault zone at the north end. There is abundant topographic evidence of numerous earlier fault—traces within the fault zone. The zone here occupies a line of uplift, the blocks on each side tilting away from the fault zone. Indirect evidence suggests that the amount of lateral movement on the San Andreas fault has been on the order of 100 miles or more.

There are no active commercial operations for the extraction of minerals in the area at the present time. Oil and gas showings are abundant in Miocene and the Pliocene sediments, and a few exploratory wells have been drilled to test the prospects of the area. No commercial production

has been found; the area has not been thoroughly explored for petroleum, but the prospects for any large accumulations of petroleum underlying the land area are not good.

INTRODUCTION

GEOLOGY OF THE POINT REYES PENINSULA, MARIN COUNTY, CALIFORNIA

ALAN J. GALLOWAY[1]

---

[1]Geologist, California Academy of Sciences, San Francisco.

The isolated triangle of land called the Point Reyes Peninsula is one of the most picturesque and dramatic spots in California. High rugged cliffs pounded by the sea; secluded coves populated by sea lions, seals, and seabirds; a long, exposed wind-swept beach; quiet sheltered beaches and estuaries; gently rolling, grassy hills; a high forested ridge; and the long, narrow, partly submerged trough of the great San Andreas fault, all combine to make the Point Reyes Peninsula a magnificent natural region with great scenic, historic, scientific, and recreational value. Although summers in this geological island may be foggy and windy, a visit to Point Reyes on a warm sunny day in April or May, made more beautiful with spring wildflowers, or on a bright fall day will be long remembered. The major portion of this unique area is now preserved as the Point Reyes National Seashore, a 64,000 acre park within sight of San Francisco.

This book describes the geology of the Point Reyes Pensinsula, and it is designed to be both a comprehensive report for the geologist and a source of information for the interested layman, who can more fully enjoy the area today by knowing how it came to be. This introduction is a generalized summary of the main report.

The Point Reyes Peninsula can be divided conveniently into four areas:

(1) The long northwest-trending depression occupied by Tomales Bay and Bolinas Lagoon and the strip of land between them.

(2) The high forested Inverness Ridge and its extensions from Tomales Point to Bolinas Mesa.

(3) The rolling grassy pastureland west of the ridge, including the major sand beaches.

(4) The rugged ridge of Point Reyes itself.

Each of these landscapes is a product of its geological composition (the rocks) and its geological history; the main features of the peninsula are directly related to the geology.

The Point Reyes Peninsula is divided from the Coast Ranges of the mainland by a long straight depression, called here the Olema trough, extending from Tomales Bay to Bolinas Lagoon. This trough serves as a natural highway diverting traffic northwest and southeast, while the hills to the west of it and the two arms of the sea form barriers to western travel.

At the shock of the great San Francisco earthquake of April 18, 1906, a crack in the ground was formed all the way up the valley from Bolinas Lagoon to Tomales Bay. This dramatically drew attention to the fact that this long depression is the site of the great San Andreas fault.

In this earthquake, the land on the west side of the fault moved northwestward relative to the land on the east side. There was little or no vertical movement. The greatest measured horizontal movement took place not near San Francisco, but in the Point Reyes Peninsula near the little town of Point Reyes Station, where the displacement amounted to 20 feet.

The 1906 earthquake crack can still be identified today. Along its course can be seen the curious topographic forms caused by the fault; little ponds perched on the tops or sides of hills, valleys without streams, and long straight low hills. As one studies the long valleys, however, it soon becomes evident that there have been many earlier earthquake cracks like that produced in the 1906 quake. In some places, the belt of fault topography is as much as a mile wide. The remains of the old cracks are too indistinct to be counted, but it is clear that there has been a tremendous amount of recurrent movement along this zone of weakness. Shattering of the rocks by continuous earth movements has weakened their resistance to erosion by rain, stream, and ocean, resulting in the formation of the long straight depression. Highway 1 traverses the San Andreas fault zone from Stinson Beach to the north end of Tomales Bay where the fault runs out to sea.

The dramatic evidence of faulting in the Olema trough leads to speculation as to how far the block of the earth's crust carrying the Point Reyes Peninsula has moved northward relative to the mainland during geologic times. Geologists hold widely varying views as to the amount of cumulative displacement on the San Andreas fault; some holding that it has been only of the order of a few miles, while others (with whom the writer is inclined to agree) suggest that it may have been of the order of 100 miles or more.

One reason for this latter view is the fact that the Point Reyes Peninsula is a little geological "island" of its own. On the adjacent "mainland" the rocks are "Franciscan", the familiar buff sandstones, reddish cherts, and green serpentines that are to be seen in San Francisco and along Highway 1 to Stinson Beach. These rocks are entirely different in appearance and age from the younger granite and white shales which make up most of the Point Reyes Peninsula; there is just no similarity between the two, and the discontinuity occurs along the fault. Another reason is the evidence for repeated faulting to be seen in the long depression described above.

The available evidence suggests that in the past 25 million years the land west of the San Andreas fault has been moving northward at a rate averaging 1/2 inch per year, which means that, in the 65 million years since the oldest sedimentary rocks were deposited on the Point Reyes Peninsula, the movement on the fault could have amounted to hundreds of mites. When the rocks of the white cliffs of Drakes Bay were being deposited under the sea, the Point Reyes Peninsula probably was in the ocean looking like one of the Channel Islands and was many miles south of where it now is located, relative to the mainland.

The rocks exposed in the Olema trough (San Andreas fault zone) are mostly Franciscan sandstones, cherts, and serpentines of the Coast Ranges which have been broken and shattered by the faulting. Overlying these rocks are much younger sands and gravels that were deposited in streams and ponds or at the bay margin in the fault zone or were deposited in the sea at the south end of the trough. These latter marine deposits, known as the Merced Formation, extend along the north and west sides of Bolinas Lagoon with the ocean.

To the visitor descending the Sir Francis Drake Highway from the east toward Olema, the Point Reyes Peninsula rises up as a dark forested ridge across his line of travel. This is Inverness Ridge, which extends from Tomales Point in the north to Bolinas Mesa in the south. The outstanding topographic feature of the Inverness Ridge is Mount Wittenburg (elevation 1407 feet), highest point in the Point Reyes Peninsula.

The backbone of this high ridge is formed of granite which on the surface extends from Tomales Point as far south as Mount Wittenburg, but over a large part of this area the granite is difficult to see because of the thick cover of soil and vegetation. (The term granite, as used in this introduction for simplicity, includes several varieties of granitic rocks described later.) The granite can be seen in the road cut of the Sir Francis Drake Highway immediately south of Inverness, also on the north side of the highway between Inverness and Tomales Bay State Park, and on top of Mount Vision. The granite is most grandly exposed in the ocean-facing cliffs of Tomales Point and Point Reyes. Here the hardness and toughness of the rock defends the land against the erosion of the breakers, but it is being gradually broken down as is evident from the many isolated rocks, stacks, and islets that can be seen in the surf. Good places to see the battle between the granite and ocean are the south-central and eastern parts of Point Reyes and McClures Beach on Tomales Point. The granite of Inverness Ridge and the similar granite of Point Reyes are about 80 million years old.

The oldest rocks in the Point Reyes Peninsula are schist, quartzite, and crystalline limestone (marble) that are found in small isolated patches surrounded by the granite of Inverness Ridge. These rocks were originally shale, sandstone, and limestone, respectively, that were engulfed by the molten granite about 80 million years ago. Since the original rocks were invaded by the molten granite, they must of course have been older originally than 80 million years, but how much older we do not know. The heat and pressure caused by the granite intrusion changed, or metamorphosed, the original shales and clays into schists, the sandstones into quartzite, and the calcareous sediments into crystalline limestone or marble. Being embedded in the mass of granite, these metamorphic rocks are harder to see than the other rocks of the Peninsula. *Crystalline limestone* may be seen in the field to the north of the Limantour—Inverness Park Road, west of the church but on the north side of the road. The limestone is harder than the surrounding rock and stands out in the field as white boulders. There are old lime kilns here too. This is private land at the time of writing; permission is needed to go on the land. [The well-known so-called "Russian" lime kilns are in the San Andreas fault zone; the limestone rock there belongs to the "Franciscan" group of rocks typical of the mainland Coast Ranges and not found on the peninsula]. *Schists* can conveniently be seen at the south end of McClures Beach; they do not make prominent outcrops because they are generally softer than the surrounding granite rock.

Southward from Mount Wittenburg the granite of Inverness Ridge is covered by an increasing thickness of younger, light-colored, marine shales that extend to Bolinas Mesa and Duxbury Reef. Similar shales and sandstone cover the lower western slopes of the ridge and extend onto the northern part of the ridge in the vicinity of the Kehoe Ranch. Ten to 15 million years ago, these sedimentary rocks, called the Monterey Shale and the Laird Sandstone, entirely covered the granite of Inverness Ridge but were later eroded from the northern part. The Laird Sandstone is a thin unit that was deposited directly on the granite; the Monterey Shale was subsequently deposited over the sandstone. The Laird Sandstone can be seen west of the road between Inverness and McClures Beach, 3/5 mile south of Kehoe Ranch. These soft sandstones are composed mainly of eroded fragments of granite; the sandstones resemble weathered granite, for which they are readily mistaken. The Monterey Shale is seen in the cliffs west of Bolinas, at Duxbury Reef, and in the sea cliffs northward to Drakes Bay. To the north, these shales become very flinty and cherty; the flinty rocks may be seen in the cliff at the Pig Ranch. In the cliffs and hills around Double Point, the Monterey shales are involved in a huge landslide nearly 4 miles long and at least a mile wide. The landscape of the slide area differs considerably from that developed elsewhere on the Monterey Shale. Extremely large blocks of shale have broken off from the main body of rock, have been tilted, rotated, and contorted, and are slowly sliding down into the sea. The tilting of the shale blocks has impounded a number of small lakes, an uncommon sight in coastal California.

On the west side of the forested Inverness Ridge, the traveller comes down to open windswept pastureland that stretches southward to the rocky promontory of Point Reyes. The smooth contours of this area can be attributed to the relative softness of the underlying light-colored siltstones and claystones. These rocks are the Drakes Bay Formation, which is younger than, and overlies, the Monterey Shale; the Drakes Bay Formation is 5 to 10 million years old. Very little in the way of rock is to be seen while driving across these grassy slopes, but the gently rolling topography ends abruptly at the famous "white banckes and cliffes" of Drakes Bay which Sir Francis Drake saw in 1579 and likened to the chalk cliffs of England. The cliffs are made of claystones and siltstones of the Drakes Bay Formation, which may be readily examined by walking along the beach in either direction from the parking lot at Drakes Beach. These sedimentary rocks overlying the granite have been folded into a broad shallow elongate bowl extending from Inverness Ridge to Point Reyes. The centerline of the bowl runs northwest-southwest through the western part of Drakes Estero.

The smooth pastureland has been cut into by the many arms of Drakes Estero and the Estero de Limantour. These are drowned river valleys that were flooded by the sea as the land slowly sank and by the rise of sea level following the melting of the glaciers of the last ice age. The long sand bar of Limantour Spit has been extended across the mouths of the esteros by the slow westward drift of sand along the shore of Drakes Bay. Another, much smaller, spit extends eastward from the west side of the mouth of Drakes Estero. These shifting sand bars are continually modifying the passage into the esteros.

The west margin of the pasturelands is the great, 10-mile-long Point Reyes Beach, a magnificent place to visit, but a very dangerous place for swimming. The wide, sandy beach is open to the sweep of the prevailing northwest winds and a strong surf and undertow are usually present. Behind the beach are high sand dunes, partly stabilized by vegetation, but in places blowing well inland. A mile south of the turn-off to Drakes Beach, the Sir Francis Drake Highway crosses an old dune ridge, and at Point Reyes the blowing sand has been heaped high against the north flank of the ridge.

At the seaward end of the Point Reyes Peninsula is the rugged rock promontory of Point Reyes itself, the most dramatic feature of the peninsula. The high, rugged ridge is due partly to the hardness of its constituent granite and conglomerate and partly to uplift along a fault under the ocean. Point Reyes is principally a mass of granite similar to the granite of Inverness Ridge. Overlying parts of the granite are large patches of conglomerate, a hard sedimentary rock made up largely of rounded cobbles and pebbles cemented together. A spectacular conglomerate is beautifully exposed at the parking lot above the Point Reyes lighthouse and all the way down past the lighthouse to the foaming surf. [Coast Guard permission required to enter this area] While most of the rounded pebbles are about egg-sized, some large blocks of granite several feet in diameter are to be seen, indicating that granite cliffs were not far away when the conglomerate was laid down. The Point Reyes Conglomerate is younger than the granite but older than the Laird Sandstone and Monterey Formation. The conglomerate is found at Point Reyes and nowhere else in the peninsula.

Geologic Story

We have described the main areas of the Point Reyes Peninsula and the kinds of rocks found in each area. The history of these rocks is a complex story that must be reconstructed from fragmentary evidence.

The oldest rocks in the Point Reyes Peninsula are the crystalline limestones, quartzites, and schists found embedded in the granite between Mount Wittenburg and Inverness. These rocks were deposited as layers of sand and clay and soft lime, just as sands and muds accumulate in shallow seas today. There must have been a great thickness of these deposits, sufficient to bury deeply the rocks that now remain. [For more detail, please see figure 5 in the section titled "Geologic History."]

Millions of years later, the sediments had become compacted and perhaps had been uplifted and folded by great earth movements. They were invaded from beneath by a mass of molten rock that solidified into granite. The heat and pressure caused by this granite intrusion changed, or "metamorphosed", the old sedimentary rocks into the hard quartzites and crystalline schists and crystalline limestones of which we now see remnants. Their age is unknown. They must be older than the molten granite that later engulfed them, which is about 80 million years old, so the limestones, quartzites, and schists are older than 80 million years, which makes them of quite a respectable age even on the geological time scale. The granite, a familiar hard gray rock made up of interlocking small crystals, today is exposed continuously between Tomales Point and Mount Wittenburg near Olema, and it forms the prominent cliffs at Point Reyes.

The solidified granite and its covering of metamorphosed sediments were lifted up to form mountains, which were then eroded by wind and rain. Probably most of the metamorphosed sediments and part of the granite had been eroded away when the sea started to encroach again on the land some 60 million years ago. Conglomerate of about this age lies on the Point Reyes granite. The sea invaded further, and some 15 to 5 million years ago the widespread sands and shales were laid down that now are found at the surface west of Inverness Ridge to Point Reyes, and south from Mount Wittenburg to near Bolinas.

Later the sea retreated and sands and gravels of about 5 million years in age seem to have been deposited only in the vicinity of Bolinas. Since that time, most of the area has been above the sea; and wind, waves, and rain are again at work, eroding the rocks grain by grain and transporting the grains into the sea to form new layers of sediment.

For tens of millions of years, while these sedimentary rocks were being deposited, the area that is now the Point Reyes Peninsula was moving slowly northward along the great San Andreas fault. Close to the coastline, one can see evidences of fairly recent vertical movements in the marine terraces and the drowned valleys. These earth movements have continued until just yesterday, geologically speaking, in the Point Reyes Peninsula; and they are still going on, invisibly, slowly, today.

Location and Extent of Area

The Point Reyes Peninsula, a roughly triangular piece of land that extends westward into the Pacific Ocean, lies about 30 miles north of San Francisco. The peninsula is joined to the mainland by the linear, trough-like Olema Valley, the drowned extensions of which are occupied by Tomales Bay and Bolinas Lagoon. The long northeast side of the triangle, from the town of Bolinas to Tomales Point, is nearly 30 miles as the crow flies. From Inverness to the west end of Point Reyes, the width of the triangle is about 12 miles. The triangular peninsula is approximately 100 square miles in area (figure 1 and photo 1). Five United States Geological Survey 7-1/2—minute topographic quadrangles, Bolinas, Double Point, Inverness, Tomales, and Drakes Bay, extending from latitude 37°52'30" N. to latitude 38°15'00" N., and from longitude 122°37'30" W. to longitude 123°00'00" W., cover the area.

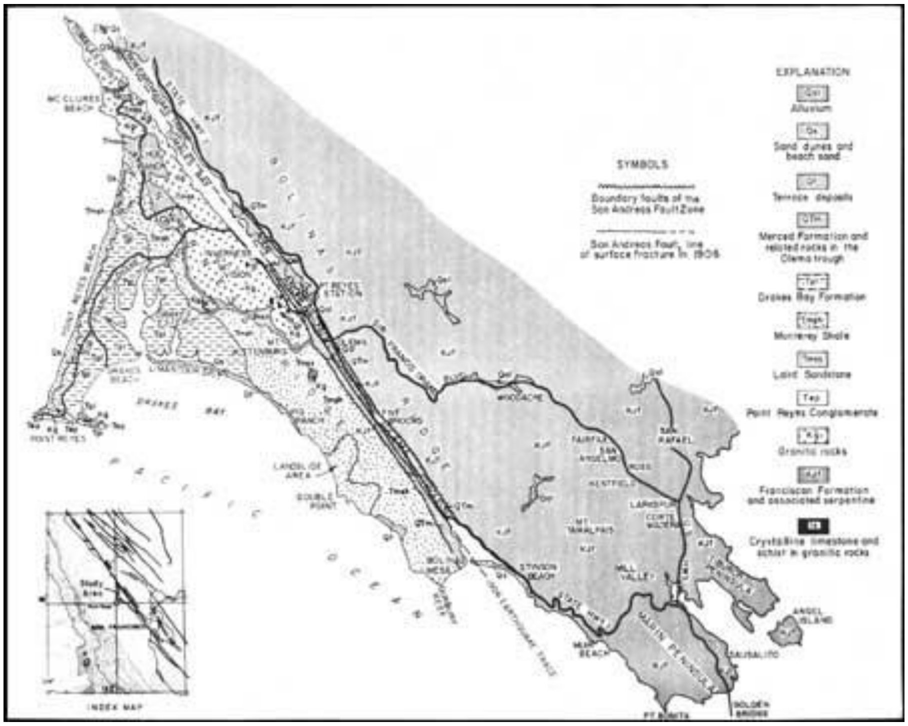


Figure 1. Generalized geologic map of Point Reyes Peninsula and adjacent area, Marin County, California. *Modified from Galloway, 1966, p. 432. (click on image for a PDF version)*

Photo 1. Aerial view of western Marin County and Point Reyes; view northwest from near Stinson Beach. The San Andreas fault zone occupies the trough lying between Bolinas Lagoon in the foreground and Tamales Bay in the upper right. *Photo by Clyde Sunderland Aerial Photographers, Oakland*

This unique area encompasses the long, narrow, partly submerged trough of the great San Andreas fault, the high forested Inverness Ridge, the rolling grassy pastureland west of the ridge with the long exposed wind-swept beach on the west and the sheltered beaches and estuaries on the south, and the rugged promontory of Point Reyes with its high rugged cliffs. Each of these landscape forms is a product of its geological composition (the rocks) and its geological history. The major portion of this scenic area, 64,000 acres, is now preserved as the Point Reyes National Seashore.

The principal settlement in the area is Point Reyes Station, at the head of Tomales Bay. Other settlements are Olema, Inveress, and Bolinas, summer resorts with small permanent populations. These towns are served by the Sir Francis Drake Highway, from San Anselmo to Point Reyes, and by State Highway 1, from San Francisco to Olema and Point Reyes Station. The area can also be reached by the Panoramic Highway from San Francisco across the south slope of Mount Tamalpais to Stinson Beach.

The area mapped and described in this report includes the Point Reyes Peninsula and the adjacent portion of the San Andreas fault zone. The Franciscan terrane that lies east of the natural boundary caused by the fault zone is not covered in this report.

Point Reyes Peninsula is distinguished from the other coastal areas west of the San Andreas fault largely by being a distinct, nearly sea-girt, tract of land separated from the mainland by the valley created by the fault zone, and by having a varied geology entirely different from that of the mainland. These factors have resulted in the peninsula having a distinct character of its own, geologically, botanically, and agriculturally.

Geologically, Point Reyes Peninsula is distinctive because:

(1) Together with Bodega Head it is the last northward appearance of the granitic-metamorphic core complex (Page, 1966).

(2) It is an isolated area where, because of the almost complete absence of Tertiary cover on the rocks east of the San Andreas fault zone, the granitic-metamorphic and the Franciscan eugeosynclinal (associated with volcanism) core complexes are juxtaposed in dramatic contrast.

(3) It is the locale of the maximum known movement on the San Andreas fault in the 1906 earthquake.

Field Investigation and Mapping

Two hundred and thirty days of field work were completed during the years 1959-1965, using as a base the U.S. Geological Survey topographic quadrangles on the scale of 1:24,000. Complete vertical aerial photo coverage was obtained from 1952 aerial photographs of the U.S. Geological Survey, series GS—UX. These photographs were studied stereoscopically and used for locating field observations. Oblique aerial photographs were used to study the cliff faces. Rock samples were studied under binocular microscope, and thin sections were made of selected igneous and metamorphic rocks for petrological study. Numerous rock samples were washed and examined for microfaunal content.

The original land survey of the area was based on the Spanish ranchos. There is no surveyed grid of sections, townships, and ranges. Consequently many localities described by the writer and earlier writers are identified only by reference to nearby ranches. Table 14 presents the latitude, longitude, and earlier names of many ranches and localities and identifies the ranches mentioned by Gilbert (1908).

Previous Geologic Work

The first scientific mention of the geology of the Point Reyes Peninsula is found in the "Report of the Superintendent of the Coast Survey" for 1855 by Blake (1856). This report included a geologic map and cross section of Point Reyes and vicinity. Blake also wrote a geological report for the Pacific Railroad Exploration and Surveys of 1857, and in both reports he mentions the granite and limestone of Tomales Bay.

Whitney (1865) mentions the area briefly in Volume 1 of "Geological Survey of California", and Brewer (1930) in "Up and Down California in 1860-1864" describes his visit to the peninsula while working for Whitney.

In 1899 F. M. Anderson published a paper entitled, "The Geology of the Point Reyes Peninsula" in the University of California Bulletin of the Department of Geology. This was the first description of the general geology, but his work did not extend east or south of Bear Valley. Nevertheless, it is of great value to later geologists, and the hand specimens he collected in the course of his field work can still be seen at the University of California at Berkeley.

The 1906 San Francisco earthquake caused a fracture and offset in the surface of the ground along the whole course of the San Andreas fault through Olema Valley. Consequently, the area figures prominently in the "Report of the State Earthquake Investigation Commission" (Lawson, and others, 1908). In this report G. K. Gilbert vividly described the phenomena visible along the Olema Valley.

A portion of the area south of latitude 38° N. is briefly described by A.C. Lawson in the San Francisco Folio published by the U.S. Geological Survey in 1914. Charles E. Weaver published "Geology of the Coast Ranges immediately north of the San Francisco Bay Region" in 1949, covering the area north of latitude 38° N.

Bulletin 154 of the California State Division of Mines, "Geology of the San Francisco Bay Counties", published in 1951, includes articles by Oliver E. Bowen, Jr., which summarize the information available at that time and add original observations. Bulletin 154 also contains a report by N.L. Taliaferro in which the geology of the peninsula is discussed along with that of the rest of the Bay Area.

For future students of the geology of the Point Reyes Peninsula, it seems desirable to mention some of the more important geological maps of the area which have been published. The first reliable geological map (scale 1:125,000) was included in "The Geology of the Point Reyes Peninsula" by Anderson (1899). The map, which covers only the area north of latitude 38° N., is a remarkable piece of work considering that no accurate topographic base was available.

Map No. 4 in the Atlas of the State Earthquake Investigation Commission Report (1908) shows the trace of the 1906 rupture through Marin County as well as San Francisco and San Mateo Counties.

Lawson (1914) included a geological map of the Tamalpais quadrangle on the scale of 1:62,500 in the San Francisco Folio of the U.S. Geological Survey. This map included the southern portion of the Point Reyes Peninsula as far north as latitude 38° N. and as far west as longitude 122°45' W. On this scale not much detail is shown, but the accompanying text in Lawson's inimitable style is well worth study.

California Division of Mines Bulletin 118 (Douglas, 1943, p. 621) contains a small map showing fairly detailed geology around Bolinas. This informative map is derived from Douglas and Rhoades (1915).

Weaver (1949) includes a geologic map on a scale of 1:62,500 using the Point Reyes 15-minute quadrangle as a base. This map extends only a short distance south of latitude 38° N.

A map derived from Harold J. Gluskoter's 1962 Ph.D. thesis at the University of California was published in 1969 by the California Division of Mines and Geology as Map Sheet 11, on a scale of about 1:40,000. This is an excellent detailed map, but the Point Reyes Peninsula portion does not extend north of latitude 38° N. or west of longitude 122°45' W.

Acknowledgments

So many people have assisted the writer in different ways in the preparation of this report that it would be impossible to list them all; indeed it is with much diffidence that any names are mentioned for fear of omitting some important contributor.

The scientific staff of the California Academy of Sciences has been consistently helpful; in particular, the writer is much in debted to Dr. G Dallas Hanna, Dr. Leo Hertlein and Dr. Peter U. Rodda. Mrs. Robert Neff and Mrs. Enid Cook kindly transcribed the field notes and typed the manuscript, two tedious tasks.

Much assistance has come from members of the staff of the California Division of Mines and Geology and from a number of geologists with the U.S. Geological Survey at Menlo Park, California.

The Texas Company and Standard Oil Company of California have been generous with information; Shell Oil Company, the writer's former employer, supplied much information; E. H. Stinemeyer of that Company contributed invaluable micropaleontologic data.

Many members of the faculty of the University of California, Berkeley, and Stanford University have contributed. In particular, the writer is indebted to Dr. Robert Compton of Stanford University for assistance in the study of igneous and metamorphc rocks. To Mr. Charles Chesterman of the State Division of Mines and Geology, he is indebted for descriptions of numerous thin sections of igneous rocks from the area. Several collectors supplied fossils found in the area; in particular the writer is grateful to Mr. C. L. Richard of San Francisco, who brought to attention the interesting callianassids from the Monterey Shale at Agate Beach near Bolinas. These fossils were identified by Mr. Dustin Chivers of the California Academy of Sciences.

Dr. W. S. Cooper assisted the writer in studying the sand dunes and old beach deposits of Point Reyes beach and Mr. Michael Lampen was of invaluable assistance in compiling the bibliography.

To numerous land owners of the Point Reyes Peninsula, the writer is grateful for permission to enter their properties. The National Park Service and the Vedanta Society have been most cooperative in this respect.

The writer takes this opportunity to thank everyone who has helped him.

GEOGRAPHY

Topography

The peninsula is dominated by Inverness Ridge, a line of wooded hills which extends in a southeast-northwest direction along the eastern edge of the area. The highest point on this ridge is Mt. Wittenburg (elevation 1407 feet), about 2 miles west of Olema. The second highest peak, Point Reyes Hill (elevation 1336 feet), is west of Point Reyes Station. Inverness Ridge slopes steeply eastward into the Olema Valley and less steeply westward to the ocean. The ridge is being actively eroded by streams, which form deep, steep-sided canyons. At the top of the ridge, remnants of rounded, mature land forms of earlier erosion cycles can be seen.

Inverness Ridge ends to the northwest in the granitic bluffs of Tomales Point. On the southeast it merges into Bolinas Mesa, an uplifted, wave-cut platform of Monterey Shale. The ridge is cut through from north to south near Olema by Bear Valley, a low pass of less than 400 feet elevation.

West of the ridge in the latitude of Inverness, the country becomes lower, open, and rolling and is dominated by Drakes and Limantour Esteros (estuaries), a system of drowned valleys invaded from the south by the sea. At the west edge of this low country, Point Reyes Beach, a nearly straight, sandy beach 12 miles long, connects Tomales Point and Point Reyes.

Point Reyes, the southern anchor of this beach, is one of the most remarkable features of the peninsula. Running east-west, across the prevailing northwest structural grain of the terrain, it stands majestically at the south end of the low dairy-farming country (photo 2).

Photo 2. Aerial view north toward Point Reyes. On the left, perched near the water, is the lighthouse. The bedded sedimentary rocks at the left (west) end of the Point are Paleocene conglomerates, which lie on Mesozoic granitic rock. In the middle distance, the Drakes Bay Formation (Pliocene) fills a syncline which is marked by the drowned valley of Drakes Estero. The San Andreas fault zone is just beyond the first dark-colored distant ridge. *Photo courtesy Aero Photographers, Sausalito.*

The eastern boundary of the peninsula, the long straight depression in which lie Bolinas Lagoon, Tomales Bay, and Olema Valley, is the most striking topographic feature (photo 1). The early geologists recognized that this depression was the expression of a major fault, but it was not until the San Francisco earthquake of 1906 that the geological significance of this fault was fully realized. After that earthquake took place, the greatest recorded lateral movement along the fault was near Point Reyes Station, where the ground moved 20 feet northwestward on the west side of the fault, relative to the ground on the east side of the fault. This dramatically drew attention to the fact that the long depression was the San Andreas fault zone. The rupture in the soil could be traced all the way from Bolinas through Olema Valley to the south end of Tomales Bay. Many text-book examples of fault topography, including ridges, sags, hollows, and ponds could be identified along the fault trace.

On the west coast of the peninsula about 6 miles northwest of Duxbury Point, several small freshwater lakes occupy a series of basins formed in landslides by rotation of large blocks of Monterey Shale which slid downslope toward the sea.

Mud Lake, at the crest of the ridge, west of Five Brooks, is probably in a large fault sag, as it lies between two prominent fracture traces. Gilbert (1908, p. 76) reported that this lake emptied quickly at the time of the 1906 earthquake. The water apparently emerged on the east side of the ridge, three-quarters of a mile away, presumably along a fault crack. Clague (1969) suggests that Mud Lake could also be of a landslide origin.

Drainage

The main drainage of the area is determined by the dominant Inverness Ridge. Small streams descend the east slope of this ridge into Olema Valley, where they flow either northwest into Tomales Bay or southeast into Bolinas Lagoon. On the west side of the ridge larger streams, such as Arroya Honda and Bear Valley Creek, descend to the ocean.

The drainage pattern is generally dendritic with consequent main streams. As would be expected in an area with so much recent earth movement, however, there are many drainage anomalies. The most striking of these are in the San Andreas fault zone. In the southern part of the fault zone, 6 miles northwest of Bolinas, Pine Gulch Creek and Olema Creek run side-by-side for 2 miles at nearly the same elevation on parallel courses about a quarter mile apart, but they flow in opposite directions. Each of these streams has eroded its course in an old fault trace—Pine Gulch Creek on the southwest side of the San Andreas fault zone and Olema Creek on the northeast side.

Farther to the south, Pine Gulch Creek follows a remarkable course. Near Woodville it leaves the San Andreas fault zone which would seem to be its natural location. The creek cuts southwestward into the hills, where it describes an elongated arc turning northeastward to debouche into Bolinas Lagoon halfway down its western side. It seems most likely that the anomalous course is due to capture by a stream that originally occupied the lower part of the present course and that was rejuvenated by uplift of the land or fall in sea level.

The short streams which flow from the Inverness Ridge into the San Andreas fault zone are, for the most part, approximately normal to the ridge, but there are some anomalous exceptions which flow southeast instead of northeast. These are associated with extensive fracture traces, visible in aerial photographs, which are considered to be branches of the San Andreas fault traversing the peninsula to the west. These are discussed in the section on "Faulting" and are shown on plate 1.

Several of the main streams, which flow from the south half of Inverness Ridge to the ocean, follow a north-south trending course, instead of a southwest course that would be expected from the topography and the general structural dip. Examples of these stream courses are the Arroya Honda, Alamea Creek which meets the ocean just north of Double Point, and the central portion of Bear Valley Creek. The reason for these anomalous directions is not clear. However, the stream courses in question are associated with the older land forms present, for instance, in the central part of Bear Valley. Further study of the old topography might show that these are antecedent or superimposed stream courses.

Many of the streams flow the year round in spite of the rainless summer. During the dry season they are fed by the summer fogs, which are intercepted by the forest trees. After a thick fog, the ground under a large tree in the forest is as wet as though it had been raining; where there are no trees, the ground will remain dry.

In the low, rolling dairyfarm lands, west of the Inverness Ridge and north of Point Reyes, there are no streams of any consequence.

Climate

The climate of Point Reyes Peninsula is characterized by cool, dry, foggy summers and cool, rainy winters. The fogs cool the area in the summer well below the temperatures a few miles inland. Inverness Ridge forms a barrier to the fog, and often in the summer the area west of the ridge will be shrouded in thick fog, while Olema Valley is sunny.

The proximity of the Pacific Ocean tends to reduce the average seasonal range of temperature. At Point Reyes Lighthouse the difference between the mean daily January and September atmospheric temperatures is less than 7° F. At Petaluma, 25 miles inland, the difference between the mean daily January and September temperatures is 19.3° F (table 1; figure 2). The temperature of the ocean shows very little variation over the year. Table 2 compares surface water temperatures at North Farallon Island with those at the Golden Gate.

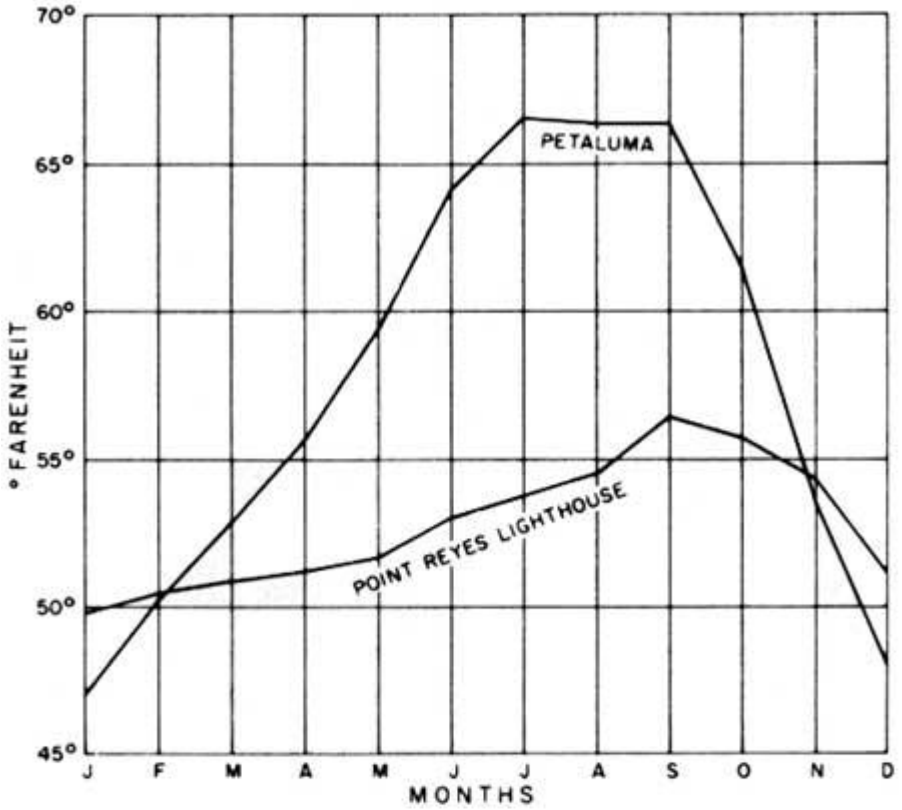


Figure 2. Mean daily atmospheric temperature by months, Point Reyes Lighthouse and Petaluma.

Table 1. Mean daily atmospheric temperature in degrees Fahrenheit by months, Point Reyes Lighthouse and Petaluma[1].

	No. years	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
Point Reyes Lighthouse (elevation 510 ft.)	52	49.8	50.4	50.8	51.1	51.7	53.0	538	54.5	56.5	55.8	54.4	51.1	52.7
Petaluma (elevation 10 ft.)	30	47.0	50.2	52.9	55.6	59.5	64.1	66.5	66.3	66.3	61.5	53.7	48.2	57.7

[1]U.S. Weather Bureau.

Table 2. Surface water temperatures in degrees Fahrenheit, North Farallon Island and Golden Gate[1].

	Jan.	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug*	*Sept.*	*Oct*	*Nov.*	*Dec.*	*Mean*	*Max.*	*Min.*

NORTH FARALLON ISLAND, 1926-1960															
Mean	53.1	52.9	52.9	52.2	52.4	53.3	54.0	54.8	56.2	55.9	54.7	54.0	53.9		
Maximum	59	57	59	59	60	64	60	64.	66	64	63	59		66	
Minimum	49	48	46	46	48	48	49	54	51	50	48	48			46
SAN FRANCISCO (FORT POINT) - GOLDEN GATE, 1922-1960															
Mean	50.9	51.7	53.2	54.5	55.8	57.5	58.7	59.6	60.2	59.0	55.6	52.6	55.8		
Maximum	58	58	60	63	64	68	66	66	65	65.	62	61		68	
Minimum	41	44	48	49	50	51	51	50	50	50	50	46			41

[1]U.S. Coast and Geodetic Survey.

Rainfall is greatly affected by the topography; for instance, at Point Reyes Lighthouse, the average annual rainfall over the past 64 years is only 19.55 inches, while at Point Reyes Station east of Inverness Ridge, the average annual rainfall between 1923 and 1936 was 29.90 inches (table 3).

Table 3. Mean monthly precipitation in inches, Point Reyes Lighthouse, Point Reyes Station, and Petaluma.[1]

	No. years	*Jan.*	*Feb.*	*Mar.*	*Apr.*	*May*	*June*	*July*	*Aug*	*Sept.*	*Oct.*	*Nov.*	*Dec.*	*Year*
Point Reyes Lighthouse (elevation 510 ft.)	64	3.86	3.04	2.68	1.50	0.84	0.26	0.06	0.04	0.47	1.23	2.26	3.31	19.55
Point Reyes Station (elevation 31 ft.)	13[2]	5.93	5.86	3.23	2.31	1.08	0.38	0.01	0.01	0.11	1.70	4.09	5.19	29.90
Petaluma (elevation 10 ft.)	30	5.29	4.49	3.32	1.77	0.63	0.21	T	0.03	0.17	1.08	2.18	4.93	24.10

[1]U.S. Weather Bureau.
[2]Record ends 1936.
T=Trace

Vegetation

Inverness Ridge is densely forested on its higher slopes, with the Douglas fir *(Pseudotsuga menziesii)* dominant at the south end, and the Bishop pine *(Pinus muricata)* dominant at the north end. On the slopes below these forests, coast live oak *Quercus agrifolia),* California laurel *(Umbellularia californica),* and buckeye *(Aesculus californica)* are found in the drier areas, and tanbark oak *(Lithocarpus densiflorus)* and madrone *(Arbutus menziesii)* are found in the moister areas. Redwoods *(Sequoia sempervirens)* are not found in the Point Reyes Peninsula west of the

San Andreas fault zone. This anomaly seems to be connected with the relative dryness of the soil formed on the Monterey Shale.

Poison Oak *(Rhus diversiloba),* coyote brush *(Baccharis pilularis),* sticky monkey flower *(Mimulus aurantiacus),* wild lilac *(Ceanothus thrysiflorus),* California sagebrush *(Artemisia californica),* and coffee berry *(Rhamnus californica)* form a dense, brush cover on the lower slopes. Wild currant *(Ribes sanguineum)* is found in moist places.

On the windswept ocean bluffs, many of these coastal brush plants have a depressed, windblown form, and some have assumed a low or creeping habit. This is particularly noticeable at Point Reyes headland where the coyote brush, which inland may be a large shrub five to ten feet high, forms a low mat only a few inches high.

The flat coastal areas form grasslands, as do many of the flatter hilltops near the coast. These grassy areas cleared for agricultural purposes revert to brushland when not grazed or regularly cleared.

The vegetation of the peninsula has been described in detail by Howell (1949), in a comprehensive work which includes some excellent photographs of Point Reyes terrane and flora. Howell describes 61 species of plants from the Point Reyes Peninsula which are not found elsewhere in Marin County. This is attributed to the very different geologic histories of Point Reyes and the rest of Marin County.

DESCRIPTIVE GEOLOGY

Metamorphic Rocks

The oldest rocks on the Point Reyes Peninsula are small patches of mica schist, quartzite, and crystalline limestone which are scattered through the outcrop of granitic rocks along Inverness Ridge from Mt. Wittenburg to Tomales Point (photo 3). These are clearly the remnants of a sedimentary series into which the granitic rocks were intruded. Most of the outcrop areas are too small to be outlined on the geologic map (plate 1), but the more important localities are indicated by symbol. No metamorphic rocks were found in the granitic outcrop at Point Reyes proper.

Photo 3. Metamorphic rocks in the sea cliff near Kehoe Ranch.

According to Weaver (1949a, p. 18), the metamorphic rocks closely resemble the Sur Series of the Santa Lucia (Monterey and San Luis Obispo Counties), Gabilan (Monterey and San Benito Counties), and Santa Cruz (Santa Cruz County) Ranges (Trask, 1926).

AREAL DISTRIBUTION

These pre-intrusive rocks of the Point Reyes Peninsula are not well exposed due to deep weathering and the dense vegetation cover on most of the outcrop area. It seems likely that the pre-intrusive sediments of the Point Reyes Peninsula were originally at least as extensive as the present outcrop of granitic rocks. Erosion subsequent to the granitic intrusion has been very deep so that only scattered patches of metamorphic rock remain. A study of the distribution of these patches of metamorphic rock on the eroded surface of the granitic pluton does not reveal any significant pattern.

LITHOLOGY

For purposes of description, the metamorphic rocks are divided into two groups: schist and limestone. In the field the two occur together in places, but the limestone is distinctive enough to merit separate discussion. The amount of quartzite exposed is insignificant relative to the schist and limestone.

Schist

Numerous small outcrops of schist are scattered through the granitic rock of Inverness Ridge, and the more important localities are indicated on the map by a symbol (sch). Interbedded in the schists are minor amounts of fine-grained biotitic quartzites. Sillimanite, garnet, wollastonite, and diopside are found in several outcrops where calcium-rich schists are interlayered with the more common biotite schists.

The schists are closely related to the surrounding granitic rocks and usually contain injections and stringers of granitic material. Often there is no clear boundary between the schists and the surrounding plutonic rock; the schist gradually merges into the surrounding granite, leaving traces in the form of unusual minerals enclosed in the plutonic rock.

Some unusual types of schists from Shell Beach on Tomales Bay include calc-schists containing quartz, wollastonite, diopside, and scapolite, and quartz biotite schists containing quartz, biotite, diopside, and amphibole (F.J. Turner, personal communication). These rocks were probably derived from interbedded pelitic sediments (and) impure limestones. The presence of oligoclase in the biotite schists indicates an advanced grade of metamorphism in the almandine zone of the greenschist facies (Charles Chesterman, personal communication).

Compton (1966, p. 286) concluded that the metamorphic rocks represent platform-type sedimentary rocks. This and the abundance of dolomitic rocks indicate that they are not metamorphosed rocks of the Franciscan Formation.

Limestone

Crystalline limestone occurs at several places in the granitic rocks of Inverness Ridge. It often shows distinct bedding and is interbedded with schist, demonstrating its sedimentary origin. All gradations, from fine-grained to coarsely crystalline types, are found; flakes and crystals of graphite are common. The principal limestone occurrences are described below from south to north.

The Mt. Wittenburg exposure, on the southeast flank of Mt. Wittenburg at an elevation of about 600 feet, is mentioned by Anderson (1899, p. 133), who regarded it as Franciscan foraminiferal limestone similar to that found in the fault zone and on the San Francisco peninsula—Calera limestone. However, the rock resembles the other metamorphic limestone occurrences and does not have the typical Calera foraminifera, so that, in view of its position within the plutonic rocks, it seems logical to regard it as part of the pre-intrusive metamorphic rocks. Thin sections of rock from this exposure consist of calc-silicate rock, complexly veined and variable in grain size and texture, containing wollastonite and diopside as well as calcite.

The Noren, Haggerty Gulch, and Lockhart exposures may be contiguous, but the thick cover of vegetation makes it impossible to connect them with any certainty. Therefore, they are shown separately on the geologic map. Weaver's map (1949a, plate 9) shows these exposures forming a single outcrop about a mile long and 1000 feet wide, but no doubt he meant to indicate only that this was a general area in which limestone outcrops were to be found. Outcrops in all three areas consist of relatively thin beds of crystalline limestone interbedded with schist and impregnated with stringers of aplite and granitic rock. The Noren exposure is described in some detail by Ver Planck (1955, p. 265-266) with particular emphasis on the scheelite which is present here with the limestone. The limestone is medium-grained and in thin section is seen to consist largely of calcite with grains of quartz, sphene, chalcedony, and phlogopite.

On the north side of Haggerty Gulch, 2000 feet west of Sir Francis Drake Highway at Inverness Park, exposures of limestone are interbedded with schists and permeated with pegmatite and granitic stringers. These exposures are probably continuous with those at the Lockhart Ranch (described below) but, due to the ground cover, they cannot be connected in the field and are, therefore, shown separately on the map. The limestone is coarsely crystalline in part, with veins of clear white calcite in a groundmass of darker material. It shows streaks of color resembling bedding.

The Lockhart exposure of limestone is at the summit of Drake's Summit Road leading west from Inverness Park to the Laguna Ranch, the Lockhart exposure of crystalline limestone is found. There are remains of old limekilns here, as well as at Inverness Park, and this is believed to be the exposure referred to by Whitney (1865) and Blake (1856 and 1857). It was also described by Ver Planck (1955, p. 259) and mentioned in Eckel (1933, p. 353), Anderson (1899, p. 131) and Weaver (1949a, p. 19; 1949b, p. 16, 89). The largest exposure at the Lockhart locality is about 40 feet long and 20 feet high, but the total area covered by limestone boulders is about 30 acres. The limestone is coarsely crystalline and banded, with some of the dark bands containing scales of biotite. Scales of graphite are common. In thin section the rock consists largely of equigranular calcite and includes grains of quartz, hornblende, orthoclase and limonite (after pyrite).

The Bender exposure is about 2500 feet west of the Sir Francis Drake Highway on the creek which flows into Tomales Bay at Willow Point. Scheelite, which was described by Ver Planck (1955, p. 265-266), occurs in the exposure. Ver Planck described the exposure as "A roof pendant composed of coarsely crystalline white limestone and biotite schist....in intrusive contact with quartz diorite. The limestone, which contains sparsely distributed flakes of graphite, lies on the east side of the roof pendant and schist is on the west side."

The metamorphosed limestone in this locality may have economic value and is discussed further under "Economic Geology." These metamorphosed limestone exposures are an integral part of the series of metamorphosed sediments that includes the schists and quartzites; they are intimately associated with schists and the whole is permeated with material from the intrusive granitic pluton.

STRATIGRAPHY

Thickness of the metamorphic beds cannot be estimated because the outcrops consist of isolated patches surrounded by plutonic rock. The patches of metamorphic rocks represent what originally must have been a thick and widespread sedimentary formation into which the plutonic rock was intruded.

The metamorphic rocks must be older than the pluton which has intruded them. The age of the granitic rocks at Point Reyes Coast Guard Lifeboat Station has been determined as early Upper Cretaceous, or 83.9 million years (Curtis and others, 1958). If the pluton of Inverness Ridge is of the same age, as seems likely, the sediments represented here by the metamorphic rocks are older than early Upper Cretaceous; no fossils have yet been found in them.

Weaver (1949a, p. 18) has correlated these rocks with the pre-Cretaceous Sur Series of the Santa Lucia, Gabilan, and Santa Cruz Ranges (Trask, 1926). The only evidence for this correlation lies in their general lithologic similarity and the fact that both sets of metamorphic rocks are engulfed in plutons of roughly the same age (Curtis and others, 1958). The Sur Series is believed by W.S. Durham (personal communication, 1964) to be of Paleozoic age, based on the presence of crinoid plates in some of the limestones. Bowen and Gray (1959) record the finding of "indistinct forms suggestive of cup corals" and "rocks suggestive of crinoidal calcarenities" in the similar limestones of the Northern Gabilan Range of California.

Granitic Rocks

The term Bodega diorite was applied by Osmond (1904) to the granitic rocks of Point Reyes, Tomales Point, and Bodega Head. On the basis of priority it would appear that this name should be applied to the granitic rocks exposed in the Point Reyes Peninsula. However, because these latter exposures are separated by the ocean from the Bodega exposure, and because they are not diorites, but range in composition from quartz diorite to adamellite, the name seems inappropriate. Curtis and others (1958) referred to a rock from Point Reyes as Point Reyes granodiorite, but this does not qualify as a formal name. No new name is proposed here for these rocks; they will be referred to in general as the granitic rocks of the Point Reyes Peninsula.

AREAL DISTRIBUTION

Granitic rocks form the backbone of the Point Reyes Peninsula, being exposed along the north half of Inverness Ridge from Tomales Point as far south as Mt. Wittenburg, with an inlier to the south in Bear Valley, a total distance of nearly 20 miles. They also occur in a separate area at Point Reyes. Granitic rocks of Point Reyes extend northward under the Pliocene cover. Four miles north of Point Reyes the granite is 1370 feet below sea level as indicated by core hole borings. No information is available on the subsurface extent westward of the main Inverness Ridge body of granitic rock. The nature of the connection, if any, between these two similar bodies of plutonic rock is unknown. However, it seems reasonable to assume they are both part of the same pluton.

LITHOLOGY

The granitic rocks, when fresh, are usually gray, medium-grained, and form rounded and sometimes craggy rock outcrops. On the west flank of Mt. Vision some more resistant zones of the granite stand out conspicuously in linear fashion. Generally, unweathered material is found only in the seacliffs. Weathering on the land surface usually has been very deep, leaving a granitic, sandy residue that is hard to distinguish in the field from the basal Miocene sand, which is also granitic. Many road cuts show more than 20 feet of weathered granite, and one core hole drilled near the top of Inverness Ridge encountered weathered granitic rock at a depth of 60 feet.

As a result of this deep weathering and the fact that most of the area is under cultivation or is covered with brush and trees, it is impossible to get a true statistical idea of the constituents of the pluton. The geologist in the field can only examine specimens from the few localities where good fresh rock can be obtained in the field. The results of this work, therefore, may not be representative of the whole pluton.

The plutonic body underlying Tomales Point and Invernes Ridge ranges in composition from quartz diorite through granodiorite to adamellite. Granodiorite and adamellite are also exposed at Point Reyes. Good exposures are insufficient to justify an estimate of the relative proportions of quartz diorite, granodiorite, and adamellite.

Many variations of these rock types occur in the outcrops, including pegmatites and aplites. Thin pegmatite veins are common. A leucocratic variety of adamellite, consisting of about 65 percent feldspar and 30 percent quartz, is fairly common. When deeply weathered, it is sometimes quarried locally as gravel for road surfacing.

Hand specimens and thin sections of the granitic rocks were examined and described by Charles W. Chesterman (written communication, 1965).

Biotite quartz diorite, one of the more common types of plutonic rocks exposed on the Point Reyes Peninsula, has a hypidiomorphic-granular texture, is medium-grained, of a medium gray with a color index less than 30. It is composed of 40 percent acid andesine, 35 to 40 percent quartz, 15 percent biotite, and 5 percent accessory minerals, including sphene, zircon, magnetite and apatite. The andesine (An^{30-35}) occurs as twinned anhedral and subhedral grains that show slight alteration to sericite. and range in size from a fraction of a millimeter to 7 millimeters. The quartz has rounded grains that exhibit wavy extinction and contain needle-like inclusions of black tourmaline (?). The biotite is deep brown, strongly pleochroic with pleochroic halos around zircon inclusions, and slightly altered to green chlorite. Dark green hornblende generally occurs in amounts subordinate to the biotite and is entirely absent from some quartz diorite. Orthoclase is rare and is generally altered to sericite. Minor accessory minerals include sphene, zircon, and magnetite.

The adamellites on the Point Reyes Peninsula differ from the quartz diorites by containing more quartz and potash feldspar but still have a similar color index of less than 30. The texture is hypidiomorphic-granular and the grain size ranges from a few millimeters to 5 millimeters. The plagioclase is intermediate to basic oligoclase in the composition ranges of An^{20} to An^{25}. It is generally fresh and occurs in subhedral and anhedral grains that show multiple twinning. Zoning is not common, but oligoclase (An^{20-25}) grains in one specimen contain rims of clear, twinned plagioclase in the composition range of An^{5-10}. This albitic rim can be observed also on a few microcline grains, and this peculiar relationship has been interpreted as a rapakivi texture and is attributed to the assimilation of basic rock by the crystallizing adamellite magma. Microcline is fresh and occurs in subhedral and anhedral grains. Quartz occurs in rounded grains and shows weak strain features.

Biotite is a common characterizing mineral, and one specimen contained an appreciable amount of muscovite. The biotite is brownish-black and exhibits characteristic pleochroic colors. Locally, the biotite is altered to chlorite and commonly contains pleochroic halos around small zircon crystals. Hornblende, rare on the adamellites, exhibited dark green subhedral prisms in one specimen. Magnetite, apatite, and zircon constitute the minor accessory minerals.

Granodiorite has a hypidiomorphic-granular texture and is fairly even-grained. The plagioclase is zoned oligoclase with a core composition of An^{25-30}, and a rim composition of An^{15-20}. It occurs in anhedral and subhedral grains, slightly altered to sericite, and contains small inclusions of biotite. Microcline occurs in anhedral and irregular grains that show the well-developed plaid structure. Alteration to sericite is slight. Quartz exhibits a wide range in grain size and constitutes about 35 percent of the rock. Biotite occurs in strongly pleochroic, anhedral grains that contain inclusions of zircon.

Chesterman concluded that the assemblage of plutonic rocks exposed on the Point Reyes Peninsula comprises a pluton of limited compositional range from quartz diorite as the basic member through granodiorite to adamellite, the acid member. Rocks of similar composition (Darrow, 1963, p. 9 and 11) crop out at Montara Mountain, about 44 miles southeasterly from Point Reyes Peninsula. Quartz diorite (Hanna, 1952, p. 302) has been identified from the Farallon Islands, about 21 miles south of Point Reyes Station. Rocks of comparable composition, though not in place, were dredged from the continental shelf off the coast of San Francisco (Chesterman, 1952, p. 360).

From the moderately wide distribution of plutonic rocks of similar compositional range, it is reasonable to assume that this part of California is underlain by a batholith which has been deroofed in a limited area only. It can be assumed, also, that this batholith extends as far south as

Santa Cruz and includes the plutonic rocks that are exposed in and around Ben Lomond Mountain (Fitch, 1931, p. 2).

Spotts (1962) reaches similar conclusions from his studies of the zircons and other accessory minerals of the plutonic rocks of Point Reyes, Bodega Head, Farallon Islands, Montara Mountain (San Mateo County), and Ben Lomond. The rocks vary considerably in texture and in relative abundance of constituent minerals. Textures are typically hypidiomorphic to allotriomorphic granular. According to Spotts, the general similarity in heavy-mineral assemblages is evidence of the development of the isolated plutonic masses of the Coast Range batholith from closely related magmas.

STRATIGRAPHY

The highest exposure of granitic rock on Point Reyes Hill is more than 1300 feet above the lowest exposure on Tomales Bay. Although the block of plutonic rock has been tilted southwestward, it seems valid to assume that the true vertical thickness of granitic rock exposed here is on the order of 1000 feet. More than 500 feet of granitic rock are exposed at Point Reyes. The plutonic mass intruded the sedimentary rocks and metamorphosed them. The plutonic mass is overlain at Point Reyes by the Paleocene conglomerate and elsewhere by younger beds.

Curtis and others (1958), using the potassium—argon (K—Ar) method, determined the age of a specimen of granodiorite collected by Anderson (1899) from a quarry near the old Government landings at Point Reyes. (A map of 1854, now in the Bancroft Library at the University of California, shows the granite quarry to have been at the site of the present Coast Guard Lifeboat Station.) The age of this rock was determined lobe 83.9 million years, or early Upper Cretaceous. Approximately the same age was obtained for a specimen of similar rock from Gabilan Mesa in the southern Coast Ranges. (Note that the work of Kistler and others, 1963, suggests that biotite K—Ar ages in some circumstances can be too young).

Compton (personal communication, 1965) noted the close similarity between these rocks and those of Montara Mountain, the Santa Lucia Range (Monterey and San Luis Obispo Counties), and even La Panza Range (San Luis Obispo County) to the south. The age relationships of the different types of granitic rocks are undoubtedly complex; however, the exposures are insufficient to permit detailed analysis.

Franciscan Rocks

It was the original intention of the writer to exclude the Franciscan rocks from this report, because the formation is characteristic of the mainland, as distinguished from the Point Reyes Peninsula, the San Andreas fault zone separating the two. However, as the work progressed, it became desirable to map the San Andreas fault zone, as it was clear that the fault zone in this area is developed in the Franciscan Formation, either exposed or covered by younger rocks. The following remarks, therefore, pertain mainly to the Franciscan Formation of the fault zone.

AREAL DISTRIBUTION

The name Franciscan was first given to sandstones, cherts, and limestones exposed in the San Francisco and Marin Peninsulas (Lawson, 1895).

Franciscan rocks underlie the San Andreas fault zone and the terrain immediately east of the San Andreas fault zone, from the north end of Tomales Bay to the south end of Bolinas Lagoon. Within the fault zone itself, the Franciscan rocks are exposed in the topographically high area near Five Brooks. To the south, the Franciscan rocks become progressively covered by the Merced Formation and the waters of Bolinas Lagoon. To the north, they are overlain by the fresh-water deposits of the Olema Creek Formation and by terrace deposits, alluvium, and the waters of Tomales Bay. Farther northwest, the Franciscan rocks crop out at Hog Island and at Tom's Point, in the middle of the fault zone. At Tom's Point, the Franciscan rocks are overlain by beds of the Millerton Formation.

According to Daetwyler (1965, p. 115), Franciscan rocks also are present 2 miles southeast of Hog Island on the floor of Tomales Bay. Apparently Franciscan rocks occupy the whole width of the fault zone all the way from Tomales Point to Bolinas Lagoon, being covered by younger beds at the north and south ends of the zone and being exposed at the surface in the central portion.

LITHOLOGY

The Franciscan rocks of the Coast Ranges, described in detail by Bailey and others (1964), consist of a varied assemblage of graywackes, shales, cherts, limestones, conglomerates, and pillow basalts, with frequent serpentine intrusions. Graywackes predominate in the outcrop areas.

The Franciscan rocks immediately east of the San Andreas fault zone in western Marin County have been described by Gluskoter (1969). For a distance of 1-1/2 to 2 miles east of the fault zone, they consist exclusively of graywackes, with subordinate shale, dipping homoclinally eastward.

Tectonic Inclusions

In contrast, the Franciscan in the fault zone itself includes blocks of limestone, conglomerate, chert, serpentine, and green stone, as well as graywacke and shale. Exposures are very poor, since the fault zone forms a topographically low and moist area which is largely covered with vegetation. Individual rocks often stand out as rounded boulders in grassy meadows. These boulders are usually very hard, and commonly those lying side by side will be composed of entirely different or contrasting rocks. It seems that these scattered hard boulders are tectonic inclusions which have been moved along the San Andreas fault and have become separated from the original outcrops. The most conspicuous of these tectonic inclusions is the large block of Calera limestone described separately below. Other types of boulders observed in the fields along the fault zone include bronzite, conglomerate, sandstone, and both black and white limestones.

In the southern part of the fault zone where the streams have cut through the overlying Merced Formation, the Franciscan rocks are mainly greenish-blue or bluish clayey material which is probably decomposed ultrabasic igneous rock.

The largest and best known of the tectonic inclusions in the fault zone is the block of Calera limestone near Five Brooks. The history of the so-called Russian lime kilns built alongside this block has been fully described by Treganza (1951), and the geology of the deposit was described by Eckel (1933). The total quantity of limestone present in this tectonic inclusion is too small to be commercially exploited (see "Economic Geology"). It does not appear to extend far laterally and is not found in the nearby stream cut. Nearby outcrops in the fault zone appear to be mostly decomposed ultrabasic igneous rocks, represented by bluish clayey material. The limestone is clearly an isolated block that has travelled along the San Andreas fault zone. The nearest large outcrop of Calera limestone reported in the literature is in San Mateo County, more than 30 miles to the south. Possibly the Calera limestone is present under water off the Golden Gate.

Following clues provided by local residents, the writer found another group of lime kilns on the Texeira Ranch about 2 miles south of the "Russian" kilns. The limestone at the Texeira Ranch is very similar to that at Five Brooks. Road grading operations near this second group of kilns uncovered fragmentary limestone, suggesting that there is another block of Calera limestone in this vicinity, which is now covered by vegetation and soil but which has been exposed sometime during the last 100 years.

STRATIGRAPHY

In the San Andreas fault zone, the exposures of Franciscan rocks are too poor and too discontinuous to permit determination of structure or thickness. Topography suggests that the Franciscan rocks of the fault zone are cut into narrow elongated "slivers", some as large as several hundred feet long and tens of feet wide, bounded on either side by lateral faults subparallel to the fault zone.

To the east of the fault zone, the structure is relatively simple, consisting of a homocline dipping northeasterly at 35 degrees to 60 degrees. The base however is not exposed, so that no estimate of thickness is possible. Weaver (1949a) estimated the thickness of this formation east of Tomales Bay to be greater than 10,000 feet.

The origin of the rocks of the Franciscan rocks has been a subject of controversy for many years and is still unsettled. Presently it is believed that the greywackes and shales were deposited by turbidity currents in deep ocean water (Bailey, and others, 1964). The mineral grains show little chemical weathering, indicating rapid erosion and deposition. The cherts are usually associated with the volcanic rocks, suggesting a generic relationship, and other considerations suggest their formation in deep water. The volcanic rocks are often pillow lavas, typical of submarine eruptions. The limestones appear to be largely chemical precipitate, genetically associated with volcanism.

The serpentines are intrusive into the other Franciscan rocks and often appear in the form of sills, but they seem to have been emplaced as serpentine rather than fluid magma and often appear to be intruded along faults. It seems reasonable to conclude that their origin was from the peridotite of the mantle below the ocean floor.

The over-all picture, therefore, is of a succession of rocks formed in deep oceanic water and subsequently elevated orogenically to their present position, perhaps as a result of plate tectonic action along the east edge of the Pacific Ocean. The source of the sediments was the continent lying to the east of the area of accumulation; the igneous rocks have strong affinities with the ocean floor.

In the Point Reyes area, the Franciscan rocks are overlain by the Pliocene Merced Formation and the Pleistocene Millerton Formation. The base of the formation is nowhere seen. Franciscan rocks are not found west of the San Andreas fault zone—and likewise the Pliocene and Pleistocene sediments and granitic and metamorphic rocks are not found east of the San Andreas fault zone in the area adjacent to that covered by this report. Rocks ascribed to the Merced Formation by Weaver (1949a) and other authors rest on Franciscan rocks between the mouth of

Tomales Bay and Petaluma, but they are quite distinct in lithologic facies from the Merced Formation found at Bolinas and apparently were laid down in a different sedimentary basin.

The Franciscan rocks of the northern Coast Ranges include rocks which may range in age from Upper Jurassic to Upper Cretaceous (Bailey and others, 1964). No fossil evidence has been obtained to date the Franciscan rocks in the area of this report, except for the Calera limestone which occurs near Five Brooks. Foraminifera in this limestone were described by Thalmann (1943) as of Turonian age (Upper Cretaceous) and identical with the fauna of the type Calera limestone. Long before that, the Calera limestone was described as foraminiferal by Anderson (1899, p. 134) and Lawson (1895).

Tertiary Rocks

PALEOCENE

Point Reyes Conglomerate

Point Reyes is designated in this report as the type area of the Point Reyes Conglomerate, which forms the craggy, rocky outcrops which give the area a great deal of its scenic character. The rocks of this formation crop out only in the extreme western part of the peninsula, overlying the granitic rocks of Point Reyes proper. Anderson (1899) considered them to be the basal conglomerate of the Miocene. Weaver (1949a,b) mapped the outcrop as part of the Laird Sandstone, a basal Miocene sandstone of the Tomales Point area. Taliaferro (1951) and Bowen (1951) pointed out that these beds at Point Reyes could well be Eocene in age. Since then, sufficient microfossil evidence has been obtained (see below) to justify the conclusion that the beds are Paleocene in age.

Areal Distribution

The Paleocene outcrops occupy three separate areas on the higher portion of Point Reyes, the three outcrops being separated by outcrops of granitic rocks from which the Paleocene rocks have presumably been eroded. The position of these outcrops is determined by cross-faulting. The beds generally dip steeply (35 to 45 degrees) to the northwest. By reason of their relative hardness, they tend to occupy the higher points of the Point Reyes ridge, where they often form craggy or stack-like outcrops emphasized by prominent vertical jointing. The beds extend discontinuously from the extreme west end of the Point to the extreme east end.

For the purpose of definition of this new rock-stratigraphic unit, the westernmost fault block (at the Point Reyes light house) is designated the type section.

Paleocene rocks have not been found to crop out elsewhere on Point Reyes Peninsula. However, an exploratory oil well, Standard (Lockhart) Tevis #1, drilled at North Double Point 10 miles to the southeast, encountered beds which may be Paleocene. In contrast to the conglomeratic sandy facies observed in the outcrop at Point Reyes, the beds encountered in this well (from a depth of about 5010 feet to about 6587 feet) consisted of fine-grained material described as hard, slickensided shale and siltstone, which contained microfauna identified as Paleocene in age.

Lithology

The Paleocene beds exposed at Point Reyes consist for the most part of a coarse, sandy conglomerate. The largest clasts in the conglomerate (up to several feet in longest dimension) consist of subangular or only slightly rounded boulders of granitic rocks similar to the suite of granitic rocks exposed in the vicinity. Granitic fragments of all sizes occur, and the matrix is largely granitic sand, poorly sorted and generally not well cemented. Along with these angular fragments of the local granitic rocks, the conglomerate contains well-rounded pebbles (up to several inches in size) composed of very hard rocks, such as volcanic porphyries and cherts. One of these rocks, a porphyry with cream to pinkish feldspar crystals in a dark purple groundmass, is particularly distinctive and can be recognized on the present beaches in Drakes Bay, in the basal Pliocene conglomerate, and in the raised beach material at the south end of Point Reyes Beach. The well-rounded and even polished appearance of these pebbles suggests that they might have been derived from some pre-existing sedimentary formation. However, since no such formation occurs in outcrop in the vicinity, the provenance of these well-rounded pebbles is not known.

The conglomerate beds are separated by strata of laminated silty micaceous, fine sand, with an occasional thin shale layer (photo 4). Carbonized plant remains are common in the silty micaceous sand layers, and Foraminifera are found in the shaley layers. The conglomerate and sand layers are distinctly cross-bedded.

Photo 4. The Point Reyes Conglomerate near the lighthouse. Note the layering of conglomerate beds with strata of silty micaceous fine sand, which gives a channelled appearance.

Anderson (1899) notes the occurrence of a fine-grained sandy shale layer 50 to 60 feet thick near the bottom of the series in the westernmost fault block. This shows up clearly in oblique aerial photographs of the cliffs but is accessible in the field only where it extends to the top of the cliff.

Stratigraphy

The thickness of the Paleocene beds exposed at Point Reyes, based on outcrop measurements, is about 700 feet. However, the top portion has been eroded away, and the original thickness must have been greater. The shaley beds of probable Paleocene age found in the Standard (Lockhart)

Tevis #1 exploratory well at Double Point were over 1500 feet in apparent thickness, and the bottom was not reached. Steep dips in this formation were reported from the cores recovered from this well, so that the true thickness penetrated is less than 1500 feet.

The source of the material comprising the Point Reyes Conglomerate was to a large extent the local granitic complex which is exposed today. The well-rounded pebbles of exotic rocks, however, come from some unknown source. Their extremely well-rounded condition and unusual hardness suggest that they may have been derived from some older conglomerate.

The conglomerate beds are graded by grain size in units which may be tens of feet thick. The sequence of beds suggests an initial onrush of extremely coarse material down a submarine slope, accompanied by coarse sand, and followed by minor flows of micaceous sand with occasional pebbles. The upper portion of these relatively fine-grained beds are often truncated by additional conglomeratic material, suggesting renewed uplift of the source beds or instability due to accumulation of coarse material at the top of the slope, with the downward movement triggered perhaps by earthquakes. Probably both causes were at work.

The almost straight east-west alignment of the south-facing cliff of Point Reyes suggests that it is an eroded fault-line scarp downthrown to the south. The presence of such a fault is also suggested by regional gravity anomalies (Chapman and Bishop, 1968).

The exposures near the Point Reyes Lighthouse illustrate graded bedding and many other sedimentary structures. Most of the exposures are coarse-grained at this locality, with very little clayey material present. These rocks, therefore, were probably deposited under water near land, on a steep slope where landslides and turbidity currents were the chief agents of deposition. Similar rocks occur in the Carmelo Formation (Paleocene) at Point Lobos in Monterey County (Lawson, 1893; Bowen, 1965). Similar pebbles have also been dredged from Cordell Bank, 20 miles west of Point Reyes in the Pacific Ocean (Hanna, 1952).

The Point Reyes Conglomerate lies unconformably on the granitic basement at Point Reyes. It is overlain unconformably by the basal glauconitic sand of the Drakes Bay Formation of early Pliocene age. In the eastern part of the Point Reyes Peninsula, beds of Miocene age lie directly on the granitic basement, and the Paleocene Point Reyes Conglomerate is not present.

The Point Reyes Conglomerate contains a foraminiferal fauna of Paleocene age. Foraminifera from clayey beds near the base of the Point Reyes Conglomerate include the following:

Ammobaculites sp.
Ammodiscus incertus
Bathysiphon eocenica
Bathysiphon alexanderi
Cyclammina incisa
Dorothia principiensis
Gaudryina glabrata
Haplophragmoides eggeri
Haplophragmoides rugosa
Haplophragmoides trullisata
Kareriella media—aguaensis
Nodogenerina delicia
Nodosaria longiscata
Pelosina complanata

Silicosigmoilina californica
Spiroplectammina richardi
Spiroplectammina eocenica
Textularia mississippiensis
Trochammina squamata
Trochammina squamata
Verneuilina polystropha

Carbonized plant remains and seeds also have been found in these beds.

Foraminifera from the Paleocene shales in the well Standard "Tevis" #1 include:

Ammodiscus sp.
Bathysiphon sp.
Silicosigmoilina california

MIOCENE

The Miocene rocks of the Point Reyes Peninsula are difficult to study because of the poor exposures and the scarcity of fossils.

Anderson (1899) divided the Miocene rocks west of Bear Valley into three units as follows:

Unit	Description
3	White Miocene shale of the Monterey series
2	A thin-bedded, cream-colored sandstone
1	A dark, heavy conglomerate

In his basal unit 1, Anderson included the Paleocene Point Reyes Conglomerate as well as the basal conglomerate of the Miocene. His middle unit 2 comprised the basal (Laird) sandstone of the Miocene, while upper unit 3 included all the shales and mudstones which he grouped together as white Miocene shale of the Monterey series.

Weaver (1949) divided the Point Reyes Miocene beds north of Double Point into 3 units:

Unit	Description
3	Sandstone with interbedded shale and chert (300 feet thick)
2	Sandy shale (2000 feet thick)
1	Laird Sandstone (named after Laird's Landing on Tomales Bay)

Weaver's basal unit 1 as mapped included the Paleocene Point Reyes Conglomerate as well as the basal sands and conglomerate of the Miocene and of the Drakes Bay Formation. He termed units 2 and 3 Monterey Shale and added that they "grade into one another and cannot be separated."

Taliaferro (1951, p. 140) recognized the unconformity of the beds exposed at Drakes Bay upon the underlying cherts. He divided the succession as follows (unit 1 is the oldest):

Unit	Description
4	Soft sands and shales with a basal glauconitic sandstone (upper Miocene?) unconformable on underlying beds.
3	Cherts, porcelanites, organic shales, and thin hard sandstones
2	Basal sandstone
1	"Laird breccia" (possibly Eocene)

Taliaferro did not apply the name Monterey Shale to any part of the section.

In this report a modification of Taliaferro's succession has been adopted as follows (unit 1 is the oldest):

Unit	Description
4	Soft sands and shales with a basal glauconitic sandstone, Pliocene (?). Unconformable on underlying beds in the area northwest of Bear Valley; these are termed the Drakes Bay Formation in this report.
3	Cherts, porcelanites, organic shales, and thin hard sandstones. Middle to upper Miocene; termed Monterey Shale in this report.
2	Transgressive basal sandstone—Laird Sandstone (restricted) of Weaver (1949). Middle to upper Miocene.
1	Laird breccia of Taliaferro. Paleocene in age; the Point Reyes Conglomerate of this report.

Laird Sandstone

This sandstone lies on the granitic basement and below the Monterey Shale. The name Laird was first used by Weaver (1949) for the sandstone that is well exposed west of Laird's Landing on Tomales Bay. Weaver included in the Laird Sandstone (1) the conglomerates of Point Reyes herein assigned to the Paleocene and (2) the basal glauconitic sandstones of the Drakes Bay Formation. Taliaferro (1951) used the terms Laird breccia and Laird conglomerate for the Point Reyes Conglomerate but pointed out that those beds might be Eocene in age. In this report, the name Laird will be restricted to the sandstones at the base of the Monterey Shale typically found west of Laird's Landing.

Areal Distribution

The Laird Sandstone (restricted) crops out in bluffs beside the road between Abbotts Lagoon and Pierce Ranch. It is also well exposed in the sea-cliff on the west coast of the peninsula west of Laird's Landing, at the north end of Point Reyes Beach. Here it lies on the granitic rocks with a few feet of granitic conglomerate at the base and is overlain by, and interbedded with, white siliceous shale (photo 5).

Photo 5. Laird Sandstone outcrop near Laird's Landing.

It is also exposed less prominently in the central area of the peninsula, lying between the siliceous shales and the granitic basement. A road recently constructed by the National Park Service overlooking Haggerty Gulch traverses an extensive outcrop of Laird Sandstone between Mt. Wittenburg and the Drakes Summit Road and provides good exposures in the road cuts.

A sand which probably is correlative with the Laird Sandstone was found at a depth of about 4700 feet in the Standard Oil Company (Lockhart) Tevis #1 exploratory well drilled at North Double Point several miles south of its most southerly surface outcrop in Bear Valley.

Lithology

In the outcrops west of Laird's Landing, the Laird Sandstone is typically a massive medium- to coarse-grained, fairly friable sandstone with little cementation. Between the subangular quartz grains, there is usually a substantial quantity of silty material. Grains of white opaque feldspar and flakes of biotite are common. At its base, the sandstone is usually pebbly or conglomeratic, with clasts of granitic rocks.

At the top the sandstone becomes interstratified with white, silty thin-bedded, laminated siliceous shales typical of Monterey Shale; these shales soon replace the underlying sandstone but are often sandy or silty for some distance above the top of the sandstone. The color of the sandstone in field exposures is usually light brown; but at White Gulch, and in a few other exposures, the weathered sandstone appears almost white. The only fossils reported from this sandstone are casts of a few small marine pelecypods resembling *Cardium.*

The thickness of the sandstone in the type area is over 200 feet; but farther south, where the Laird Sandstone is overlain by Monterey Shale and underlain by granitic rocks of the basement complex, the sandstone seems to be much thinner in many places, although exposures are too poor for accurate measurements. It thickens again on the north flank of Mt. Wittenburg. Its apparent thickness in the exploratory well (Standard (Lockhart) Tevis #1) at North Double Point is about 100 feet.

This quartzose feldspathic sand was clearly derived in the type area from weathering of the granitic basement. In the northern part of the peninsula, the Laird Sandstone can be seen lying on the irregular surface of the granitic rocks. It seems to have been laid down in a quiet transgressive sea, advancing gently across an old irregular eroded granitic surface.

Stratigraphy

The Laird Sandstone, wherever seen in outcrop, lies unconformably on the granitic basement; but it lies above Paleocene beds in the exploratory well at North Double Point (Standard (Lockhart) Tevis #1). At Point Reyes it is not exposed, and the overlying Drakes Bay Formation lies directly on the granitic and Paleocene rocks. The upper part of the Laird Sandstone grades by interbedding into the Monterey Shale, subordinate beds of shale appearing with increasing frequency higher in the section until the section is predominantly siliceous shale with subordinate sand beds.

The youngest beds on which the Laird Sandstone rests are Paleocene in age. The oldest beds found above it are Miocene in age, assigned to the Relizian stage, but in the type area it is overlain by beds of Mohnian age. No fossils of any diagnostic value have been found in the Laird Sandstone. The fact that the Laird Sandstone passes upward conformably into middle Monterey Shale by interstratification leads to the conclusion that it is Miocene in age. Since it was deposited by a transgressive sea, it may well vary in age from place to place.

Monterey Shale

The Monterey Shale was first described by Blake (1856) from Monterey, California. The formation in the type area includes the Luisian, Mohnian, and Delmontian stages (Kleinpell, 1938; Bowen, 1965); and all of these stages are found on the Point Reyes Peninsula. Both Anderson (1899) and Weaver (1949) refer to these rocks as Monterey Shale, although Taliaferro (1951) does not use this name. It seems logical to use this well-known name for these rocks at Point Reyes, since they are lithologically similar and of the same age.

Areal Distribution

These shales cover most of the peninsula area included in the Bolinas and Double Point quadrangles, and the outcrop extends northwest between the outcrops of the granitic rocks and the Drakes Bay Formation as far north as the Kehoe Ranch in the Tomales quadrangle. The outcrop area is about 3 miles wide at the latitude of Bear Valley, narrowing rapidly northward until in the vicinity of the Home Ranch it is only 1/2 mile wide. North of the Home Ranch, it increases again to a width of 2 miles before feathering out onto the granitic high of Tomales Point.

The outcrop surface is normally smooth and covered with vegetation; but, where the shale is predominantly cherty, a number of striking crags and pinnacles have been formed by differential erosion (photo 6).

Photo 6. Craggy Monterey chert outcrop near U—Ranch.

Lithology

As pointed out by Taliaferro (1951), the Monterey Shale includes cherts, porcelanites, organic shales, and thin hard sandstones, with every variation between these types. Some shales are silty and fissile, others hard and massive, and some display a conchoidal fracture. Altogether they comprise a bewildering variety of rather similar appearing rocks, but some general groupings of lithologic types can be made.

Going from north to south in the Tomales quadrangle, nearly all the shales are thin-bedded, laminated, micaceous, and white weathering. They contain fish scales and fish remains along with molds of Foraminifera and diatoms. At the south end of this quadrangle, the shales tend to be hard and flinty and commonly blocky and flagstone-like. In the Drakes Bay quadrangle between Abbotts Lagoon and the Home Ranch, they become harder and more like flagstones. Microfaunal evidence suggests that all of the above rocks are of Mohnian age.

Immediately southeast of the Home Ranch, shales of Luisian age overlie granitic rocks in a small area between Home Ranch Creek and Glenbrook Creek. These shales are laminated, porcelaneous, and silty and do not differ markedly from the Mohnian shales, although their microfauna is unequivocally of the Luisian age. In the field they appear to be conformable with the overlying Drakes Bay Formation, though this conformity can only be apparent in view of the difference in age.

In the Inverness quadrangle southeast of Glenbrook Creek, a long outcrop of hard siliceous cherts about a mile wide extends as far southeast as Bear Valley and the Double Point quadrangle. These very hard, brittle cherts are dark grey-brown and often laminated with thin shaley or sandy interlayers. They commonly exhibit the banded "spheroids" described by Taliaferro (1934). The silica necessary to form the cherts probably was derived by solution of diatoms and other common siliceous organisms in the shales (Bramlette, 1946). The cherts are usually very contorted in the outcrop, suggesting that the whole mass of beds slid down the continental shelf while in a relatively pliable condition (Curray, 1965, figure 3). As a result of these contortions, it is impossible to map the regional attitude of these beds with any reliability (photos 7, 8).

Photo 7. Contorted Miocene cherts at U—Ranch beach. This photo was taken about 1935 during C. E. Weaver's survey. *Photo courtesy of C. L. Herald*

Photo 8. Outcrop of contorted Miocene cherts on the Laguna Ranch. Inverness Ridge lies to the right and the ocean is to the left. Down-slope sliding is suggested by the appearance of these beds.

Underlying the cherts on the slopes of Mt. Wittenburg and extending southeastward as far as Bear Valley is a bed of low-density fissile shales with plant remains, molds of Foraminifera, fish remains, and sandy interlayers near the base. This shale bed appears in the vicinity of Laguna Ranch Creek and extends southeastward, gradually widening until at Bear Valley it is about a mile wide. Anderson (1899, p. 137) took special note of these shales, as he was puzzled by the interlayers of sand in the very fine-grained shale in the outcrop on Mt. Wittenburg.

These fissile shales are Mohnian—Delmontian age, based on the foraminiferal fauna, and accordingly, the overlying cherts must be of this age or younger. The presence of Mohnian—Delmontian beds overlying the granitic rocks of Mt. Wittenburg indicates that in this vicinity the Mohnian—Delmontian beds overlap the underlying Luisian beds onto the granitic rocks. In this connection, Kleinpell (1938) states that the Mohnian lies unconformably on wide expanses of preLuisian rocks in a number of areas, including Point Reyes.

In the wedge-shaped area between Bear Valley and the San Andreas fault, a distinctive type of shale occurs in which no diagnostic fossils have been found. This shale is dark blue-grey, hard, micaceous, and fine-grained. In most of the outcrop area, the shale dips northward or northeast toward the San Andreas fault, suggesting that these beds are at least as young as the beds at the top of Mt. Wittenburg, which are of Mohnian—Delmontian age.

The large landslide area of the Lake Ranch and Wildcat Ranch is located to the southeast of the chert outcrop. Most of the shales are affected by the landslides; they overlie the cherts except in a few instances, where both cherts and shales are involved in the landslides, and are, therefore, at least as young as Mohnian—Delmontian. In lithology and appearance, the shales of the landslide area resemble the shales at Duxbury Point to the southeast.

In the Bolinas quadrangle, southeast of the Lake Ranch landslides, nearly all of the outcrop area is occupied by shales similar to those well exposed at Duxbury Point, from which Foraminifera of Delmontian age have been recovered. These thin-bedded siliceous shales and claystones are grey, lavender, or chocolate, commonly have conchoidal fracture, and in places have laminae of fine silt. They weather to grey-white. A durable member of these shales forms Duxbury Reef, which extends a mile out to sea along the south-east strike and which has been a graveyard for sailing ships (photo 9). These shales are more argillaceous than the previously described varieties and jointing is prominent. The shales commonly contain yellow-buff calcareous concretions, often flattened or elongated along the bedding planes. The shales make most of the south end of the Point Reyes Peninsula and can be traced from Duxbury Point northward along the coastal cliff section as far as the Palomarin Ranch.

Photo 9. Duxbury reef, a durable member of the Monterey Shale which extends out to sea as much as a mile. The wreck of the ship "Polaris" is seen in the center of the photo. *Photo courtesy of C. Page.*

At the Palomarin Ranch, a number of thick sandstone beds occur in an overturned syncline, which suggests that most of the Duxbury Point shales are older than the sandstones. These beds include a richly glauconitic member which may well be equivalent to the basal glauconitic sand of the Drakes Bay Formation to the north. Although it is impossible to trace the bed through the extensive landslides north of the Palomarin Ranch, displaced exposures of the glauconitic unit in the landslide area indicate that it originally extended across this area.

Stratigraphy

The total thickness of the Monterey Shale is difficult to determine since the complete section is not exposed. However, some idea of the minimum thickness can be obtained. On the coast between Duxbury Point and Bolinas Point, approximately 3500 feet of Monterey Shale is exposed in a southwesterly dipping homocline. Near the base of this section is the top of an abandoned exploratory well, Lockhart RCA 3—1, reported to be bottomed in Monterey Shale of Relizian age at a depth of 8409 feet. The true thickness of Monterey Shale represented by the sum of these two measurements is probably on the order of 8000 to 9000 feet.

The Monterey Shale thins northward due to erosion and overlap, until in the south part of the Tomales quadrangle only a thin section of upper Mohnian age overlies the Laird Sandstone, and further north it is completely absent. At the southwest extremity of the area on the Point Reyes promontory, it does not appear from under the overlapping Drakes Bay Formation, which lies on the Paleocene and the granitic basement.

The basin in which the Monterey Shale was laid down probably deepened southeastward, judging by the evidence of two deep exploratory wells, one at North Double Point and the other at Bolinas Mesa. It can be expected, therefore, that the thickness of the Monterey Shale increases in a southerly direction. Chapman and Bishop (1968) point out that the negative gravity anomaly between the Farallon Islands and the Marin Peninsula could be caused by a prism of sedimentary rocks about 2.5 miles (or 13,000 feet) thick. The anomaly extends southeastward to include the La Honda basin (San Mateo County) of Cummings and others (1962), suggesting that the Point Reyes sedimentary area is a northerly extension of the La Honda basin.

When Anderson (1899) wrote the first geological report on the Point Reyes Peninsula, the origin of the siliceous Monterey shales, at Monterey and elsewhere, was a matter of active speculation, as evidenced by the space devoted to a discussion of the origin of the shales of Point Reyes. Nearly fifty years later, Bramlette (1946) devoted an entire U.S. Geological Survey Professional Paper to the origin of the Monterey Shale. Bramlette's conclusions are applicable to the comparable shales of the Point Reyes area. The more important conclusions are summarized as follows:

(1) Most of the porcelaneous and cherty rocks of the Monterey Formation were formed through an alteration that consisted largely of a rearrangement of the silica of originally diatomaceous deposits.

(2) The thin rhythmic bedding or lamination was evidently formed at depths below that affected by appreciable wave or current action.

(3) Few lithologic zones are persistent enough to be of much value in the general correlation.

(4) Most of the foraminiferal faunules indicate depths between the upper limits of the neritic zone and the edge of the continental shelf.

(5) The evidence available seems, on the whole, to indicate conditions of temperature and rainfall not markedly different from those now existing along the California coast.

(6) The deeper basins and shallow water divides off the present coast in the region of the Channel Islands constitute such conditions of bottom topography as ore postulated for the Monterey seas.

The Monterey Shale lies conformably on the Laird Sandstone with which it merges by interbedding. In most of the area, the Laird Sandstone in turn lies on the granitic basement rocks; but in exploratory well Standard (Lockhart) Tevis #1 at North Double Point, it lies on shale of Paleocene age.

Overlying the Monterey Shale is the Drakes Bay Formation of Pliocene age. There is a pronounced angular unconformity between the Drakes Bay Formation and the Monterey cherts near the U—Ranch in the northern part of the area; but at the Home Ranch, nearer the axis of the Point Reyes syncline, the two formations appear to be conformable with the base of the Drakes Bay Formation marked only by a glauconitic sand. This conformity is, however, only apparent, since at the Home Ranch the shale is of Luisian age and the Mohnian and Delmontian are not present and the Drakes Bay Formation lies directly on beds containing fauna of the Luisian age.

Deposition of Monterey-type shales seems to have continued for a short period after the glauconitic sand at the base of the Drakes Bay Formation was laid down. These shales immediately above the glauconitic sand are lithologically very similar to the Mohnian—Delmontian shales of Duxbury Point, but must be younger.

In the overturned syncline at the Palomarin Ranch, the glauconitic sand is exposed in the outcrop, and the beds above and below it appear to be conformable. However, observations in this area are rendered uncertain by the landslides. Thus the unconformity at the base of the glauconitic sand seems to disappear to the south as the Miocene-Pliocene basin thickens.

The oldest Miocene foraminiferal fauna in the Point Reyes Peninsula outcrop of the Monterey Shale is found in beds exposed 2000 feet southeast of the Home Ranch headquarters. This is approximately Weaver's locality No. 2180 (1949, p. 76-77). Foraminifera collected include:

Baggina californica
Bolivina advena
Bulimina montereyana
Buliminella subfusiformis
Cassidulina subglobosa
Chilostomella ovoides
Globigerina bulloides
Gyroidina montereyana
Lagena sp.
Nonion sp.
Orbulina universa
Uvigerina peregrina

Valvulneria miocenica
Virgulina californiensis

In addition diatoms of the genera *Coscinodiscus* and *Isthmia* were found.

Mollusca collected include:

Anadara cf. *A. montereyana* Osmont
Cyclocardia montereyana Arnold
Pecten cf. *P. peckhami* Gabb

Weaver collected the following mollusca from this locality:

Anadara devincta Conrad
Lucina acutilineata Conrad
Spisula albaria (Conrad)
Tellina nevadensis (Anderson and Martin)
Nassarius arnoldi (Anderson)

At another locality (A.J.G. 974) 6000 feet southeast from Weaver's locality and on strike with it, a similar foraminiferal microfauna is found with the additional species:

Bolivina striatella
Bolivina brevior
Bolivina seminuda
Nonion costiferum
Nonion montereyanum
Nonionella miocenica
Valvulneria californica
Uvigernella californica
Uvigernella undulata

Also the diatoms *Actinoptychus* and *Coscinodiscus* and the radiolarian *Cenodiscus* were found. These fossils indicate a Luisian age for these beds. Similar beds containing *Pecten peckhami* and the Foraminifera *Nonion, Buliminella,* and *Robulus* are found in the center of the anticlinal structure which extends through the head of Schooner Bay.

Elsewhere the Foraminifera of the Monterey Shale generally are consistent with a Mohnian age. For example, the following middle to upper Miocene Foraminifera were found near the J. McClure Ranch headquarters (north of the Home Ranch):

Bolivina seminuda
Bulimina ovula
Nonion costiferum
Pullenia sp.
Robulus sp.
Sphaeroidina sp.
Uvigerina sp.
Valvulneria sp.

At the north end of Abbotts Lagoon (north of the Home Ranch), the following microfauna of probable upper Mohnian age were found:

Bolivina seminuda
Buliminella subfusiformis
Nonion costiferum
Pulvinulinella pacifica
Pulvinulinella gyroidinaformis
Uvigerina hootsi
Virgulina sp.

Near Mud Lake and also at McCormick Creek inland from Duxbury Point, the following microfauna were found, which suggest a Mohnian—Delmontian age:

Haplophragmoides
Trochammina sp.
Bathysiphon sp.
Gaudryina sp.
Cyclammina constrictimargo

At the top of Mt. Wittenburg, the shales yielded the following, which again suggest a Delmontian or Mohnian age:

Cyclammina cf. *C. constrictimargo*
Ammobaculites stephensoni
Haplophragmoides cf. *H. becki*
Trochammina parva

Foraminifera of lower Mohnian age have been reported in the Monterey Shale near the granite contact along the road between Inverness and Point Reyes lighthouse. A skeleton of the fish *Eclipes,* common in the late Miocene, and impressions of the small decapod crab *Pinnixa galliheri* Rathburn (photo 10) were found in this vicinity.

Photo 10. Impression of *Pinnixa galliheri* Rathburn, a decapod crab, from the late Miocene shales. *Photo by Dea Beach.*

In the vicinity of Duxbury Point, the following have been found:

Callianassa goniophthalma (mud shrimp)
Fragments of whale bone
Cetacean skull (Sirenian?)
Fragments of *Brisaster?* and *Scutellaster?*.

Foraminifera of Mohnian—Delmontian age have been found here also, including:

Bathysiphon
Dorothia?
Trochammina parva
Haplophragmoides sp.
Elphidium hannai
Gaudryina sp.

The foregoing evidence shows that a central inlier of middle Miocene (Luisian) shale at the Home Ranch is bordered to the northwest and southeast by Monterey Shale variously determined as of Mohnian or Mohnian—Delmontian age. In deep exploratory wells at North Double Point and on Bolinas Mesa, middle Miocene shales are overlain by substantial thicknesses of upper Miocene shales. Thus, it appears that the Mohnian shales overlap the Luisian shales over most of the peninsula. The outcrop of Luisian stage rocks in the inlier at the Home Ranch is probably due to local uplift; however, it must be assumed that they are present under the rocks of Mohnian age in most of the area southeast of the Home Ranch.

Other Miocene Rock Types

Clastic Dikes

Dikes composed of medium- to fine-grained sandstone are commonly found in the cherty shales of the Monterey Shale, northwest of the mouth of Bear Valley Creek, at north Wildcat Beach, in the chaotic landslide shales of south Wildcat Beach, at Double Point, and in the Duxbury-type shales at the mouth of Arroya Honda. In a number of cases, the locus of the clastic dike emplacement is the axis of a small anticlinal fold. Dikes at Wildcat Beach, Double Point, and Arroya Honda are often strongly bituminous. Some dikes pass into sills, and it is difficult to distinguish them from normal sedimentary sandstone beds.

It seems likely that these clastic dikes were injected into the shale as a slurry of sand suspended in water or oil. Large earthquakes, accompanied by landsliding, are the probable immediate cause of the disturbances which formed the dikes.

A particularly impressive bituminous sandstone dike is to be seen in the cliff on Wildcat Beach, about 5000 feet south of Wildcat Military Reservation, Double Point quadrangle (photo 11).

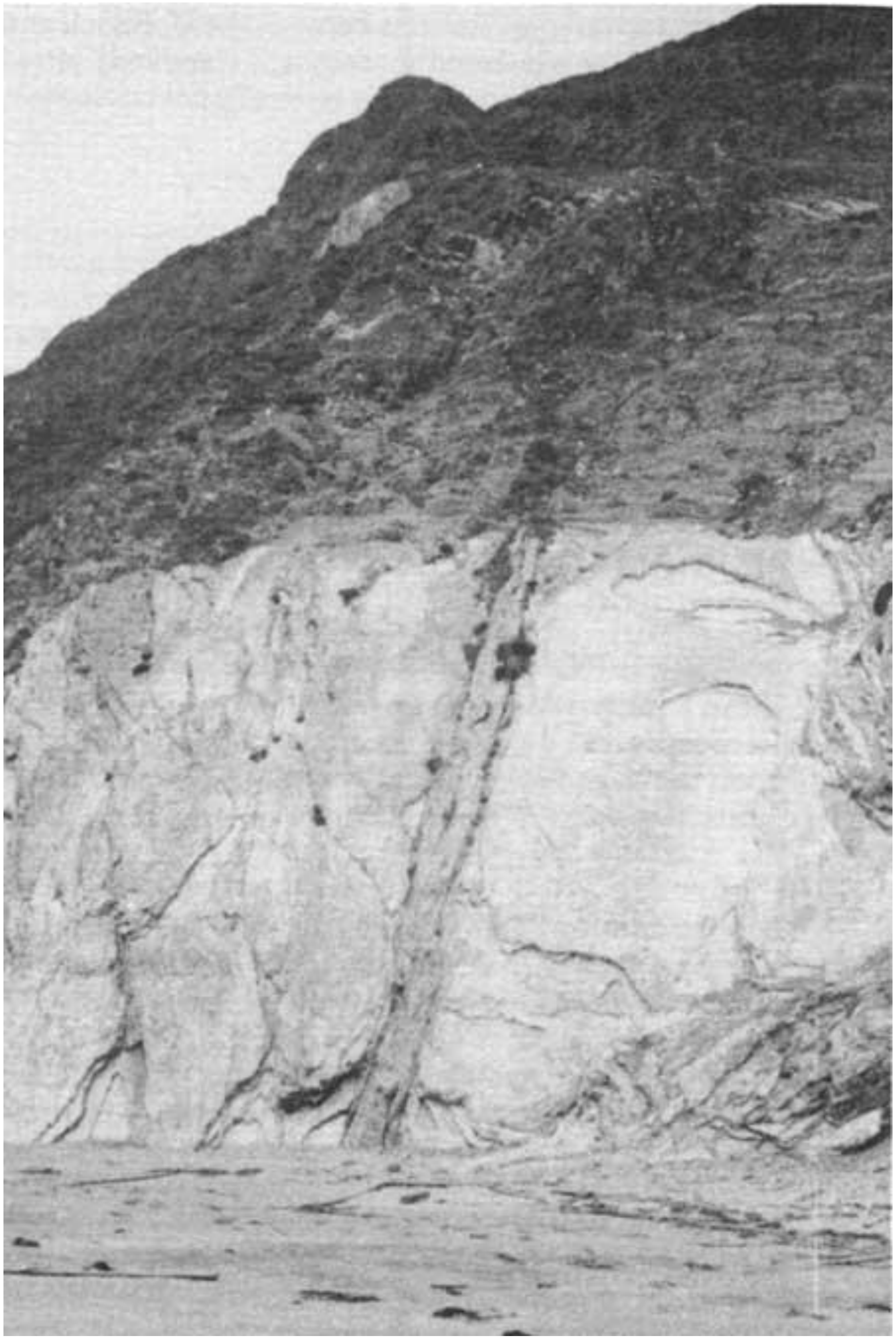


Photo 11. Bituminous sandstone dike in Monterey cherts at Wildcat Beach. The cherts are folded on a vertical axis.

Phosphatic Shales

Shales containing blebs, lenses, and laminae of phosphatic material are common in the Miocene of the Coast Ranges of California (Dickert, 1966), particularly in the beds of Luisian age. A search was made for phosphatic material in the siliceous shales of the Point Reyes Peninsula without success. Blebs of white material, similar to the phosphate blebs illustrated by Dickert, are fairly common in the beds southeast of the Home Ranch which contain a Luisian fauna; but the phosphatic material, if such it originally was, appears to have been replaced by silica, and no unequivocal phosphate was found.

Gower and Madsen (1964) reported the occurrence of phosphate nodules from the upper Miocene of the Point Reyes Peninsula; this occurrence is believed to be in the basal glauconitic sand of the Drakes Bay Formation, which contains many bone fragments as well as glauconite.

Extrusive Igneous Rocks

Basaltic and pyroclastic rocks are common in the Miocene of California. In the Point Reyes Peninsula, only two occurrences are reported:

(1) In the exploratory well (Standard (Lockhart) Tevis #1) at North Double Point volcanic material was reported at a depth between 4900 to 5000 feet.

(2) Basalt and obsidian fragments were also reported from the sea cliff between Duxbury Point and Bolinas, close to the faulted Miocene Merced Formation contact near Bolinas. The stratigraphic position of this sample is uncertain since the beds are adjacent to the San Andreas fault zone and apparently are standing vertically due to structural deformation.

According to KIeinpell (1938), volcanic material is most commonly encountered in the Miocene near the Relizian—Luisian contact. This is approximately the stratigraphic position of the material encountered in the Standard (Lockhart) Tevis #1 well. He also reports small lava flows near the coast southwest of Mt. Wittenburg, but this has not been confirmed.

PLIOCENE

The beds, which are here formally designated the Drakes Bay Formation, form the white cliffs of Drakes Bay which Sir Francis Drake saw in 1579 in the course of his circumnavigation of the globe. They reminded him of the white Cretaceous chalk cliffs of southeastern England, and he called the newly discovered land New Albion.

Drakes Bay Formation

Anderson (1899) and Weaver (1949) did not distinguish the Drakes Bay Formation but included these beds under the general term Monterey Shale. Taliaferro (1951) identified the formation clearly in a cross-section (p. 128, plate 1, cross-section IV). In the report (p. 140), Taliaferro stated that, although the age of the beds was unknown, they were probably upper Miocene, The present writer first termed the beds upper Miocene in 1962, but later evidence pointed to their being early Pliocene in age (Gallo way, 1966).

The type area and locality of the Drakes Bay Formation is the syncline lying between the granitic ridges of Inverness Ridge and Point Reyes; the Drakes Bay sea-cliff extending from Drakes Estero to the granitic outcrop at the eastern end of the Point Reyes ridge is designated as the type section (figure 3).

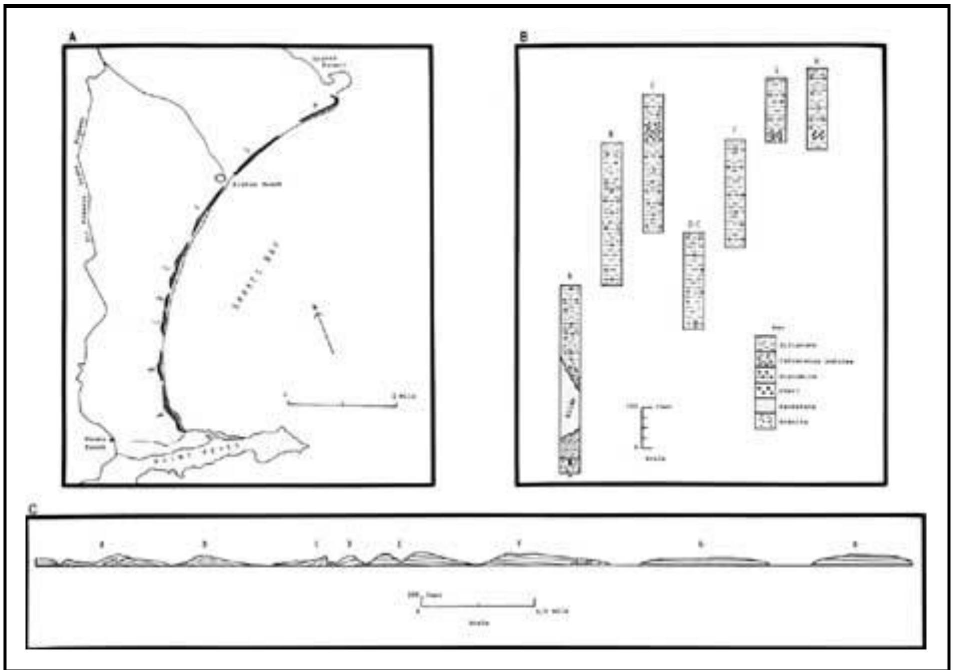


Figure 3. Type section of the Drakes Bay Formation. (a) Index map: type section is exposed in cliffs A-H. (b) Columnar sections for cliffs A-H, arranged in stratigraphic order. (c) Profile of cliffs A-H, showing dip of beds and position of beds. *(click on image for a PDF version)*

Areal Distribution

The Drakes Bay Formation occupies a synclinal area bounded on the west by the granitic promontory of Point Reyes and the Pacific Ocean, on the south by Drakes Bay, and on the east by a line from Abbotts Lagoon southeast to the U—Ranch. Discontinuous patches of the formation extend southeasterly as far as Double Point. Remnants of weathered deposits on hilltops suggest that the Drakes Bay Formation once extended over most of the Point Reyes Peninsula, and it is still the most extensive of the formations exposed on the Peninsula.

The main outcrop area forms the rolling windswept pastures that are seen from the Sir Francis Drake Highway between the head of Drakes Estero and the Point Reyes Lighthouse. Few trees grow in the outcrop area, in contrast to the thickly forested granitic outcrop of Inverness Ridge. The absence of tree cover may be partly due to the lower rainfall on the lowlands and partly to clearing by man. Exposures, except for the seacliff section, are few and small and are mostly in creek beds and road cuts. The softness of the siltstones and mudstones leads to a general rounding and softening of the contours of the hills, a feature which would also have reminded Sir Francis Drake of the Chalk Downs of southeastern England. The sandstones at the base of the formation, however, weather into resistant ledges and form prominent topographic features between the U—Ranch and the Home Ranch. The weathered sandstone is commonly pitted like weathered limestone, although it is generally not calcareous.

Lithology

At the base of the Drakes Bay Formation is a striking glauconite-bearing greensand. In many places, the concentration of glauconite is so great as to give the rock a brilliant green color. In the outcrop at east Point Reyes where the greensand lies unconformably on the granitic rocks, it has stained them a bright grass-green. The sandstone has this same color at the opposite side of the syncline, where it lies unconformably on the Miocene cherts on the beach near the U—Ranch; and a number of the inland exposures also show this unusual concentration of green glauconite.

The greensand is thickest (about 100 feet) near the Laguna Ranch; at this locality, the green color is diluted to greenish-gray by the presence of much quartzose sand. At Point Reyes it is only about 25 feet thick, and at its inland outcrop it is often thinner or represented by thicker sands containing only scattered glauconite.

The greensand, in addition to abundant glauconite, contains biotite, quartz grains, and shale pebbles, which make it harsh and rough to the touch in hand specimen. At Point Reyes it contains numerous calcite veins and is quite calcareous. Remains of fish vertebrae, bones of marine mammals, and pieces of carbonized wood have been found in the formation. At Point Reyes the Drakes Bay Formation has a thin conglomerate at the base which contains large granitic clasts and boulders of the Paleocene conglomerate. East of the Point Reyes syncline, the green sand lies on the Monterey Shale and contains shale and chert fragments derived from the underlying rocks. The glauconite of the greensand oxidizes to a distinctive rusty brown.

Overlying the greensand are thin-bedded hard chocolate-brown shales 50 to 100 feet thick, which grade upward through light-colored laminated shales interbedded with sand into the overlying tan to white siltstones and mudstones. The shale immediately overlying the greensand is in places very similar to the Monterey Shale exposed at Duxbury Point.

The main body of the Drakes Bay Formation, overlying the greensand and associated shales, consists of fine-grained, tough, compact, cream to brown siltstones interbedded with massive silty mudstones that are grey to yellowish. In general these siltstones and mudstones resemble those of the Monterey Shale, but they lack the hard siliceous shale and the rhythmic bedding of the Monterey Shale. The Drakes Bay Formation contains large rounded calcareous concretions at various levels, with the concretions being particularly numerous on the beach east of the Mendoza Ranch. Layers of fine grey to brown sand are occasionally present. The contact between mudstone below and siltstone above is often of knife-edge sharpness.

In the outcrops along the hilltops southeast of the U—Ranch, the Drakes Bay Formation is represented mostly by the basal glauconitic sand and the sandy beds overlying it; the soft siltstones and mudstones overlying the sands have apparently been largely lost by erosion. Thus the beds southeast of the U—Ranch are distinctly coarser in grain than those to the northwest.

On the geologic map, a division is made between the Drakes Bay basal sands and the overlying mudstones and siltstones; however, it must be remembered that this division is arbitrary and inexact since the two types grade into one another.

Stratigraphy

The Drakes Bay Formation occupies a syncline and feathers out to zero thickness on the two flanks of the syncline through erosion of the overlying beds. The thickest known section is that encountered by a Standard Oil Company of California core hole (Molseed #1) drilled near the junction of the road to Drakes Bay County Park and the Sir Francis Drake Highway. This core hole is reported to have encountered granite at a depth of 1620 feet; it appears to have been in the Drakes Bay Formation from the surface to a depth of at least 1543 feet, so that an apparent thickness of more than 1500 feet is present here. Since this hole is close to the axis of the syncline, dips are low and the reported thickness is believed to be close to the true thickness. The top of the formation is not present so that its original thickness is not known. Apparently a minimum thickness of about 1600 feet should be credited to it, since the core hole (Molseed #1) started at a relatively low elevation.

The basal sands of the Drakes Bay Formation increase in thickness in an easterly direction, indicating that the sands were derived from the granitic outcrop at Inverness Ridge. The claystones and mudstones could readily have been derived from the nearby Monterey Shale.

The conditions under which glauconite is formed have been the subject of much discussion. According to Emery (1960), glauconite is presently found under the sea off southern California in a general environment of oxidizing conditions, such as on submarine bank tops, ridge crests, hills that rise above shelves, and on some slopes. Glauconite accumulates very slowly in areas of detrital sediments. In the basal member of the Drakes Bay Formation, the accumulation of glauconite probably indicates shallow water conditions with very little sedimentation. The scattered glauconite in the thicker gray-green sands may be reworked, and these sands undoubtedly accumulated in shallow water.

The mudstone-siltstone series is so similar to the Monterey Shale (except for the absence of rhythmic bedding) that it probably accumulated under very similar circumstances in offshore basins of relatively deep water. The relative scarcity of fossils also suggests this type of environment.

The Drakes Bay Formation lies unconformably on the Paleocene conglomerate and the granitic basement at Point Reyes on the west side of the Point Reyes syncline, the Monterey Shale being absent in the outcrop there (photo 12). On the east side of the Point Reyes syncline, the Drakes Bay Formation lies on the Monterey cherts. A marked unconformity between the two units is exposed on the beach near the U—Ranch—the greensand with a thin basal conglomerate dipping about 7° to the west and the underlying Monterey cherts dipping 45° to the northeast (photo 13). Near the Home Ranch there is little angular unconformity apparent; and yet here the beds underlying the Drakes Bay Formation are middle Miocene in age, so that a considerable hiatus in time is indicated.

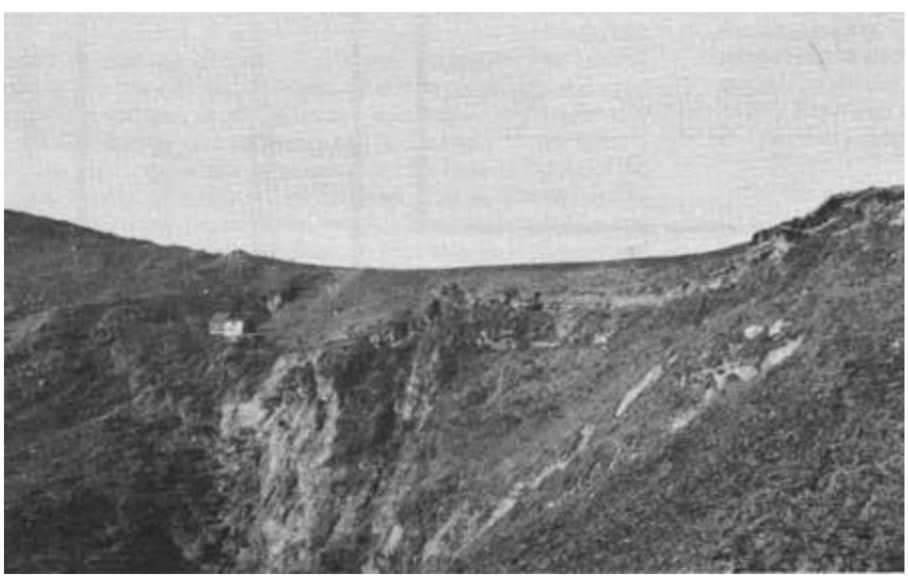


Photo 12. The basal sand of the Pliocene Drakes Bay Formation lies unconformably on the Paleocene Point Reyes Conglomerate west of the Point Reyes syncline.

Photo 13. Basal Pliocene glauconite sand (Drakes Bay Formation) lying nearly flat on Miocene Monterey chert, which dips steeply east (to the right), near U-Ranch.

Farther southeast along the coast, as far as Bear Valley, the basal glauconitic sandstones occur as outliers on the hilltops and again are clearly unconformable with the underlying Monterey cherts. South of Bear Valley the Drakes Bay Formation has been removed by erosion or is obscured by landslides.

Clague (1969) concludes that the Drakes Bay Formation originally extended southeastward from Bear Valley across the Lake Ranch landslide area, where he found discontinuous remnants of the basal glauconitic sand. At the Palomarin Ranch, south of the landslide area, the glauconitic sand crops out in a syncline and appears to be conformable with the underlying Monterey Shale of the Mohnian—Delmontian age. Lying on the Monterey Shale at several hill-top points in the Bolinas quadrangle are remnants of deposits which may have been the basal conglomerate of the Drakes Bay Formation; this also suggests that possibly the Drakes Bay Formation originally extended much more widely over the Point Reyes Peninsula than it now does.

The youngest beds on which the Drakes Bay Formation lies are late Miocene in age; and it is overlain only by sand dunes, beach deposits, and marine terrace deposits of Pleistocene to Holocene age.

Many fossils have been collected by the writer and others from the Drakes Bay Formation. These are listed below:

Vertebrates
- Vertebrae of large teleost fish cf. *Gonolytes*
- Skull of sea lion *(Otariidae)*
- Skull of dolphin
- Tooth of *Carcharodon* cf. *C. arnoldi*
- Abundant vertebrae and bones (marine mammals?)

Mollusks
Neptunea colmaensis Martin
Polinices cf. *P. lewisii*
Spisula? or *Macoma?*
Nuculana cf. *N. taphria* Dall
Solen cf. *S. sicarius* Gould
Lucina annulata or *L. acutilineata*
Megasurcula carpenteriana (Gabb)

Echinoderms
Megapetalus cf. *M. loveniodes* Clark
Ophioplocus sp.?

Foraminifers
Buliminella elegastissima
Eponides exigua

Radiolarians
Abundant

Diatoms
(See table 4)

Regarding the diatoms, Hanna (personal communication, 1969) stated:

"Those who are familiar with the distribution of these fossils will notice at once that there are present numerous species which are known to be characteristic of formations considered to be late Miocene in age. The material is light in color, chalky in texture and the non-organic constituents are largely volcanic "ash" particles. Stratigraphic evidence, however, as Mr. Galloway has shown indicates the age to be Pliocene...It is probable that this large deposit of quite fossiliferous shale is made up of material which was derived from a late Miocene deposit soon after its elevation above the sea. Evidence of such reworking of similar materials has been seen in Santa Barbara County, California, between Santa Maria and Lompoc. One of the best marker diatoms of the Pliocene is *Lithodesmium cornigerum.* This was not found in the Marin County study, a negative result possibly due to insufficient search."

Near the head of Creamery Bay, on the east side at water level, a number of carbonized cones of *Pinus lawsoniana* Axelrod, which are very similar to those of the living Monterey pine *(Pinus radiata),* have been found. The beds in which the fossil pine cones occur closely resemble the Drakes Bay Formation but could possibly be part of a younger mudflow or mud slide overlying the Drakes Bay Formation proper. These fossil pine cones are, therefore, the same age as the Drakes Bay Formation or younger. Unfortunately, none of the above fossils is particularly diagnostic as to age. Most of them could equally well be from Miocene or Pliocene beds, and some range up into the Holocene. The diatoms, according to Hanna and Wornardt (personal communications) are more indicative of upper Miocene than of lower Pliocene.

A sample of the glauconite bed at the base of the Drakes Bay Formation at Point Reyes was submitted for dating by the K/Ar method, and an absolute age of 9.3 ± 0.5 million years (m.y.) was determined. The reliability of K/Ar dating based on glauconitic sediments may result in dates that are too young (Evernden and others, 1960; Obradovich, 1965; and Wetherill, 1965). It seems unlikely that the Drakes Bay Formation has ever been deeply buried; it is now overlain only by Pleistocene or Holocene sediments. The presence of reworked glauconite, or incomplete glauconitization, will result in too high a figure, but no determination of this possibility has been made.

Table 4. Species of diatoms found in the Drakes Bay Formation at localities 1234 and 37674 (California Academy of Sciences). See photos 14 and 15.

	1234[1]	*37674*[2]
Actinocyclus ehrenbergii Ralfsi		X
Actinoptychus bismarckii Schmidt	X	
Actinoptychus grundlerii Schmidt	X	
Actinoptychus splendens (Shadboldt)	X	X
Arachnoidiscus ehrenbergii Bailey	X	X
Arachnoidiscus ornatus Ehrenberg	X	X
Aulacodiscus brownei Norman	X	X
Aulacodiscus kittoni Arnott	X	
Aulacodiscus oregonus Harvey and Bailey	X	
Auliscus pruinosus Bailey	X	
Auliscus punctatus Bailey	X	X
Auliscus sculptus Bailey	X	X
Biddulphia tuomeyi Bailey	X	X
Campylodiscus sp.		X
Cerataulus turgidus Ehrenberg	X	X
Coscinodiscus asteromphalus Ehrenberg	X	
Coscinodiscus excentricus Ehrenberg	X	X
Coscinodiscus marginatus Ehrenberg	X	X
Coscinodiscus radiatus Ehrenberg	X	X
Coscinodiscus robustus Greville		X
Coscinodiscus stellaris Roper	X	
Cymbella sp.	X	
Dossetia temperei Azpieta		X
Entopyla gigantea (Greville)	X	X
Grammatophora oceanica		X
Hyalodiscus sp.	X	
Isthmia nervosa W. Smith	X	X
Lithodesmium minusculum Grunow		X
Melosira clavigera Grunow		X
Navicula excavata Greville	X	X
Pinnularia major Kützing	X	
Ploaria petassiformis Pantocsek		X
Rhaphoneis rhombus Ehrenberg		X
Stephanopyxis sp.		X

Stictodiscus californicus Greville	X	
Stictodiscus hardmanianus Greville		X
Trachyneis aspera Ehrenberg	X	
Triceratium arcticum Brightwell	X	
Triceratium californicum Grunow	X	
Triceratium consimile Grunow		X
Triceratium elegans Greville	X	X
Triceratium montereyi Brightwell	X	X
Xanthiopyxis lacera Forti		X
Xanthiopyxis umbonatus Greville	X	X

[1]Locality 1234 (CAS): 5 miles east of Point Reyes lighthouse. Marin County. California.
[2]Locality 37674 (CAS): Drakes Reach County Park, Marin County. California; 200 feet east of parking lot at base of cliff.

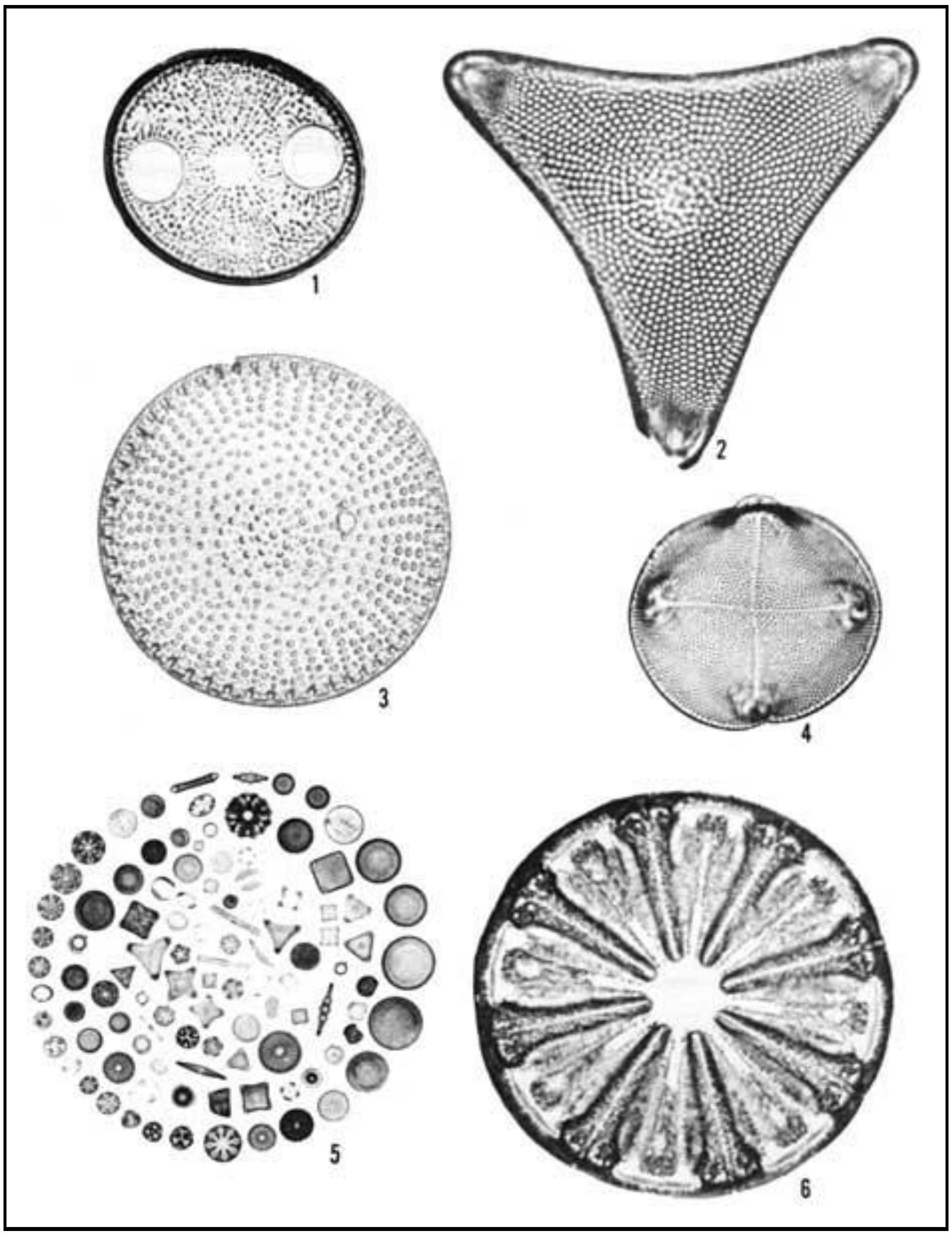


Photo 14. Diatoms from the Drakes Bay Formation. All of the species illustrated on this plate are from locality 1234 (CAS), located 5 miles east of Point Reyes lighthouse, Marin County, California (table 4). The specimens are deposited in the collection of type material of the Department of Geology, Academy of Sciences, and bear numbers 20056—20061. Figure 1—*Auliscus punctatus* Bailey; figure 2—*Triceratium arcticum* Brightwell; figure 3—*Stictodiscus californicus* Greville; figure 4—*Aulocodiscus kittoni Arnott;* figure 5—a selection of species on slide prepared by A. L. Brigger, Yucaipa, California; and figure 6—*Actinoptychus splendens* (Shadboldt). *Photos by G. D. Hanna.*

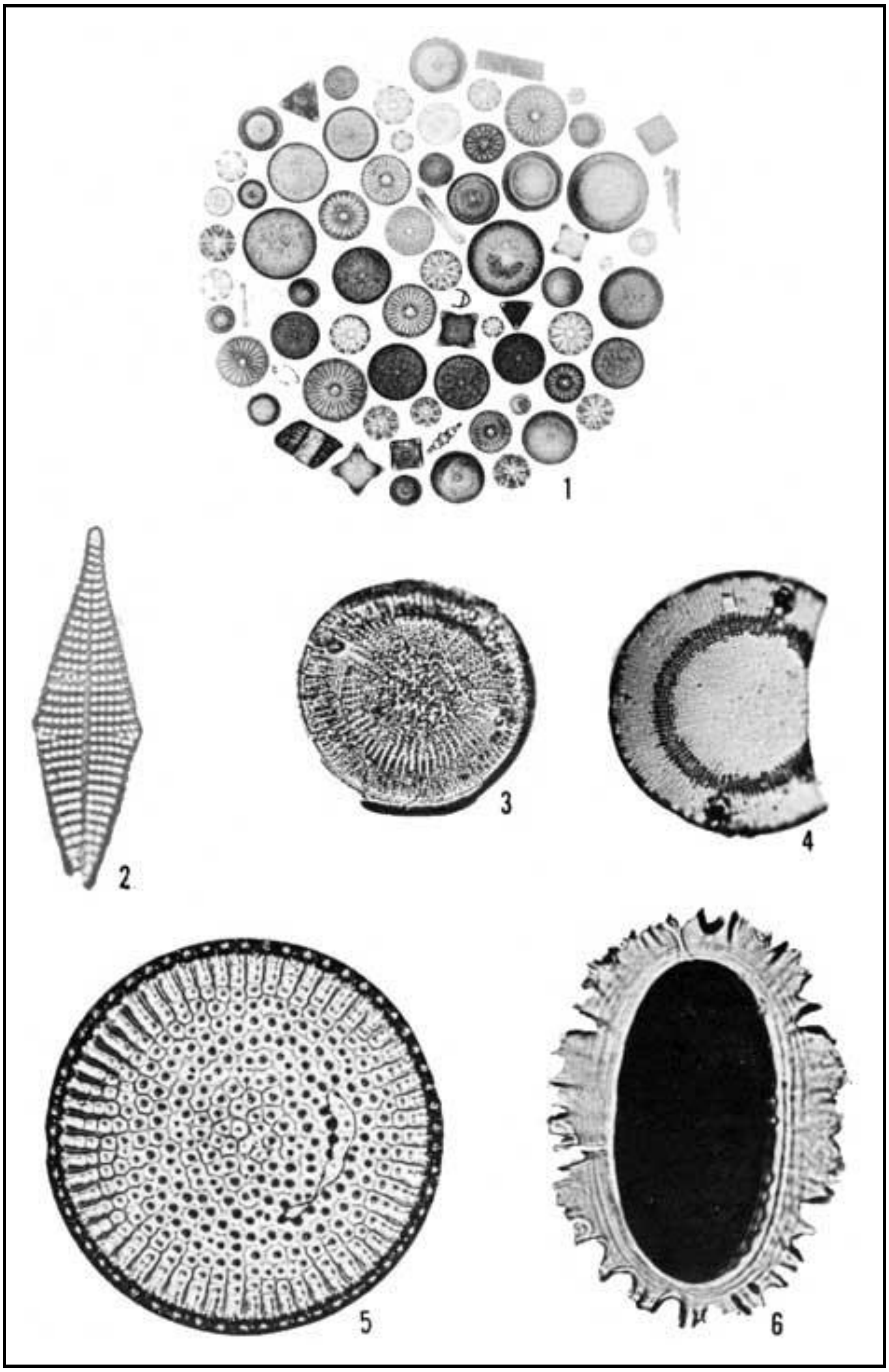


Photo 15. Diatoms from the Drakes Bay Formation, All of the species illustrated on this plate, except Figure 1, are from locality 37674 (CAS), 200 feet east of the parking lot at the base of a cliff in Drakes Beach County Park, Marin County, California. The specimens are deposited in the collection of type material of the Department of Geology, Academy of Sciences, and bear numbers 20062—20067 (table 4). Figure 1 is from locality 40972b (CAS) (table 5). Locality 40972 (CAS), marine diatomite, is in Drakes Beach County Park, Marin County, California, approximately 2 miles west of County Park Headquarters at the center of a syncline; 40972a is 10 feet above a hard resistant layer exposed at low tide; 40972b is 20 feet above the hard resistant layer exposed at low tide. Collected by A. J. Galloway and G. D. Hanna, July 7, 1968. Figure 1—a selection of species on slide prepared by A. L. Brigger, Yucaipa, California; figure 2—*Rhaphoneis rhombus* Ehrenberg; figure 3—*Aulacodiscus brownei* Norman; figure 4—*Aulacodiscus brownei* Norman; figure 5—*Stictodiscus hardmanianus* Greville; figure 6—*Dossetia temperei* Azpietia. *Photo by C. D. Hanna.*

Table 5. Species of diatoms found in the Drakes Bay Formation at locality 409721 (California Academy of Sciences). See photos 14 and 15.

Actinoptychus bismarckii Schmidt
Actinoptychus senarius Ehrenberg[2]
Actinoptychus splendens (Shadboldt)
Arachnoidiscus ehrenbergii Bailey
Arachnoidiscus ornatus Ehrenberg
Aulacodiscus brownei Norman
Aulacodiscus kittoni Arnott
Aulacodiscus oregonus Harvey and Bailey
Biddulphia sp.
Chaetoceras sp.[2]
Cocconeis lineata (Ehrenberg)[2]
Coscinodiscus asteromphalus Ehrenberg
Coscinodiscus excentricus Ehrenberg
Coscinodiscus lineatus Ehrenberg[2]
Coscinodiscus marginatus Ehrenberg
Coscinodiscus radiatus Ehrenberg
Coscinodiscus stellaris Roper
Entopyla gigantea (Greville)
Lithodesmium minusculum Grunow
Melosira clavigera Grunow
Melosira sulcata (Ehrenberg)[2]
Ploaria petassiformis Pantocsek
Podosira montereyi Grunow[2]
Rhabdonema japonicum Tempere and Brun[2]
Rhizosolenia sp.[2]

Rutilaria longicornis Tempere and Brun[2]
Stephanopyxis sp.
Surirella sp.[2]
Xanthiopyxis umbonatus Greville

---

[1]Locality 40972 (CAS): Marine diatomite, Drakes Beach, Marin County, California, approximately 2 miles west of County Park Headquarters, at the center of a syncline; 40972 is 20 feet above a hard resistant layer exposed at low tide. [2]Not found at localities 1234 and 37674.

If the 9.3 m.y. age is approximately correct, it may be compared with the following dates for the beginning of the Pliocene:

13 m.y. ± 500,000	Kulp, 1961
12-13 m.y.	Evernden and others, 1959
10 m.y.	Holmes, 1960
12 m.y.	Evernden and others, 1961

Even allowing for the fact that glauconite K/Ar ages have a tendency to be 10 to 20 percent too young, it appears that the base of the Drakes Bay Formation is approximately at the base of the Pliocene. The formation is, therefore, younger than the Monterey Shale.

It is interesting to note that Clark (1966, p. 139) reports a K/Ar date of 6.7 ± 0.5 m.y. for glauconite at the base of the Purisima Formation in the Santa Cruz area, suggesting that the Drakes Bay Formation is older than the Purisima Formation.

Cummings and others (1962, p. 195) described an unnamed member of the Monterey Formation from the La Honda basin in the Santa Cruz Mountains which "consists principally of alternating beds of siliceous and diatomaceous mudstone, and sandy siltstone or very fine-grained sandstone", brownish in color. "At the base of the member there is a light gray to greenish-gray, coarse-grained, feldspathic sandstone that is typically glauconitic". These and other particulars suggest that this unnamed formation is very similar to the Drakes Bay Formation.

Its age is believed to be late Miocene or possibly early Pliocene and may be of Delmontian age. It is thought to be unconformably on the Woodham's Shale member of the Monterey Formation, and it is overlain conformably by the Purisima Formation.

Farther south in the Felton—Santa Cruz area, Clark (1966) has described a sequence of organic mudstone beds of Relizian to Luisian age as belonging to the Monterey Formation. These mudstones are overlain unconformably by the Santa Margarita Sandstone, which in turn is overlain conformably by the Santa Cruz Mudstone. He believes the Santa Margarita Sandstone to be of Mohnian age or younger. The Santa Margarita Sandstone in this area with the overlying Santa Cruz Mudstone also resembles the Drakes Bay Formation in age and stratigraphic position. The following correlations between the Point Reyes area, the La Honda basin and the Santa Cruz—Felton area are suggested. It is noticeable that, while shales of the Mohnian stage are widespread in the Point Reyes Peninsula, being apparently transgressive over earlier Monterey shales, in the La Honda basin and in the Santa Cruz—Felton area, beds of the Mohnian stage are either absent or represented by the Santa Margarita Sandstone. According to Clark (personal communication), west of Ben Lomond Mountain (Santa Cruz County), the lower part of the Santa Cruz Mudstone may be of the Mohnian stage.

Merced Formation

The Merced Formation was named by Lawson (1893) and the type section is exposed in the cliffs at Seven Mile Beach, south of San Francisco. The presence near Bolinas of the Merced Formation is first mentioned briefly by Lawson (1908, p. 29-30) in the State Earthquake Investigation Commission report which was issued after the San Francisco earthquake of 1906. The Merced Formation at Bolinas is again mentioned by Lawson (1914) in the San Francisco folio of the United States Geological Survey and by Martin (1914, 1916). Martin (1916) gives a comprehensive review of the Pliocene of middle and northern California, in which the Merced Formation at Bolinas is included. He concludes that the section at Bolinas very closely resembles the type section at Seven Mile Beach, correlating it with the lower Merced Formation of the type section.

Areal Distribution

The Merced Formation of the Point Reyes Peninsula is confined to the San Andreas fault zone near Bolinas (Higgins, 1961) and extends for about 7 miles to the northwest. The Merced Formation is not found at the Tomales Bay end of the Olema Valley, nor is it found west of the fault zone. The Merced Formation of a rather different facies occurs in the vicinity of Dillon's Beach north of Tomales Bay, where it lies on the Franciscan rocks east of the fault zone, but not in the fault zone itself.

The similarity of the lithology and fauna of the Merced Formation at Bolinas to the type section leads to the conclusion that the Bolinas section must have been laid down in the same basin as the type section at Seven Mile Beach. It is probable, therefore, that the outcrop is continuous under the ocean between Seven Mile Beach and Bolinas. The section at Bolinas is, however, only a few hundred feet thick compared with more than 5000 feet in thickness at the type section.

The Merced Formation at Bolinas, consisting mostly of soft sands and silts, forms low-relief rounded topographic features. The sea cliffs at Bolinas, formed by the Merced Formation, are being rapidly eroded by wave action. (See section on "Erosion")

Photo 16. The Pliocene Merced Formation exposed in the sea cliff at Bolinas.

Lithology

The Merced Formation at Bolinas consists of blue-gray, soft siltstones and fine friable sandstones in the lower part, with coarser sandstones, pebble beds, and gravels, usually weathered to brown colors, in the upper part.

In view of the accessibility of the Merced Formation exposure in the sea cliff at Bolinas, it seems worthwhile to describe it in a little more detail (photo 17). The cliff section is L—shaped; the western part of the section faces south toward the ocean, and the line of cliffs trends nearly east-west. This part of the section is nearly a dip section, the beds dipping eastward at 10 degrees or less. At the channel leading into Bolinas Lagoon, the cliff line turns almost due north and faces east. Since the beds are dipping easterly, the trend of the cliff is nearly parallel to the strike. The cliffs are 100 to 140 feet high.

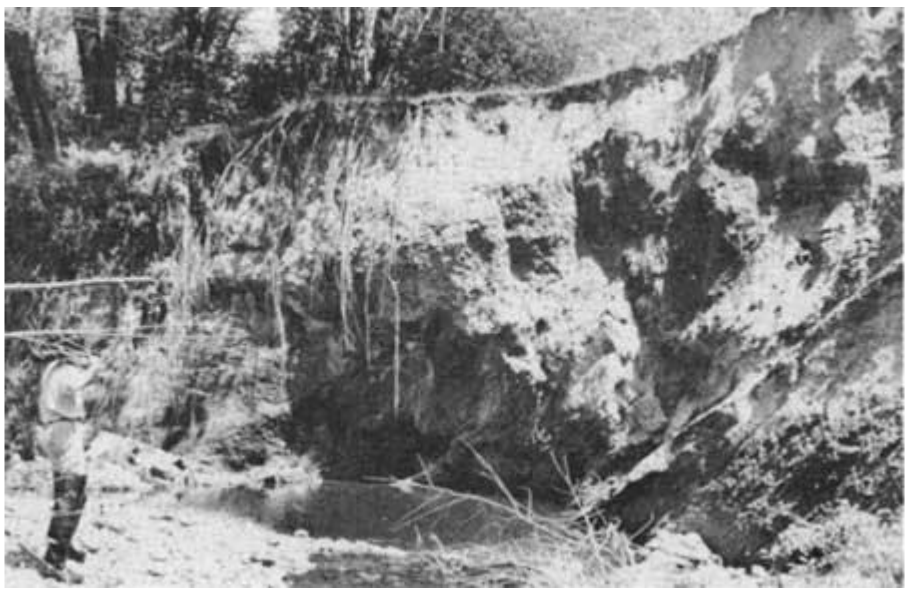


Photo 17. The Pleistocene Olema Creek Formation near Olema. Granitic material is interbedded with siltstones.

The lower part of the section, exposed in the ocean-facing cliffs, is more than 100 feet thick, and the base of the formation is not exposed. The cliffs consist of gray-blue siltstones with some fine, clayey sandstones, with occasional layers of shale fragments and scattered calcareous concretions, many of which contain fossils. The beds display some crossbedding. The base of these siltstones is not seen; the top forms a sharp contact with the overlying sandy beds. The siltstones contain abundant Foraminifera and occasional pieces of carbonized wood. Water seeps out at the contact between the siltstones and the more permeable beds which overlie them.

Above the siltstones, in the cliff facing the channel, are found about 50 feet of silty fine sands, with occasional layers of small rounded pebbles (up to about 1 inch diameter) and scattered layers of shell fragments. These sands are also crossbedded and are usually weathered tan to brown in contrast with the blue-grey siltstones on which they rest. These sands are overlain by about 80 feet of coarser weathered material, including medium to coarse sands and gravels with bands of pebbles.

Summarizing, the cliff section contains:

Top 80 feet; coarser sands and gravels, brown and tan

Middle 50 feet; silty fine sands, weathered brown

Bottom 100+ feet; base not exposed; blue-gray siltstones

Total 230+ feet

Stratigraphy

The thickness of the Merced Formation exposed in the cliff section is 230 feet, with the base not exposed. Water wells drilled in the vicinity of Bolinas have penetrated up to 300 feet of Merced Formation, starting at some point below the highest beds exposed in the seacliff. It seems that the total thickness of the Merced Formation at Bolinas is more than 300 feet and not over 500 feet. This is remarkably thin compared with the 5000 feet exposed at the type section only some 15 to 20 miles to the southeast.

The lithologic features and fossil content of the lower part of the Merced Formation at Bolinas indicate deposition under shallow water, neritic conditions, in a sea probably less than 400 feet deep. Higher in the section, the lithology indicates deposition in still shallower water until, at the top of the section, the beds resemble back-beach deposits. The coarser pebbly layers contain abundant Monterey Shale pebbles, derived from west of the San Andreas fault zone. Material was also contributed from east of the fault zone as indicated by pebbles of Franciscan chert.

Reed (1933, p. 246) points out that the Merced silts of Bolinas Bay contain large numbers of *Elphidiella hannai* a foram which is now an important part of the small living fauna of such embayments as San Francisco and Tomales Bays. We can therefore envisage the Merced silts of Bolinas as being deposited in a somewhat restricted bay, connected on the southeast with the type area of the Merced Formation. Movement on the San Andreas fault zone has to be taken into account in imagining what the situation was in Pliocene times. Assuming that right-lateral movement on this fault has continued since before Pliocene times, the Point Reyes Peninsula, at the time of deposition of the Merced Formation, will have occupied a position west of the Golden Gate, forming an enclosed shallow embayment between the peninsula block and the mainland, in which the Merced beds of the type section and also those of Bolinas were laid down.

The Merced Formation in the Point Reyes Peninsula is confined to the south end of the San Andreas fault zone near Bolinas. On the west side of the zone, it is in contact with the Monterey Shale. This contact has been described by earlier writers as depositional, but the present writer could find no evidence of this; it seems more likely that the contact, which is practically a straight line, is a fault, the west boundary fault of the San Andreas fault zone. (The boundary could also be due to a fault line scarp forming a topographic feature in Merced time.) (Gluskoter, 1962, also concludes that the Merced—Monterey contact is a fault contact). The Merced beds lie unconformably on the Franciscan rocks of the fault zone facies, a relationship which is clearly exposed in the San Andreas fault zone northwest of Bolinas.

In the eastern part of the fault zone, the Merced Formation also seems to be delimited by a fault-line scarp, in this case the east boundary fault as determined by the writer. The Merced Formation is not found on the graywacke facies of the Franciscan that lies east of the fault zone. Only beaches and sandspits overlie the Merced Formation in the Bolinas area.

The type section of the Merced Formation at Seven Mile Beach south of San Francisco is regarded by Glen (1959) as ranging from middle Pliocene to lower Pleistocene. The Merced Formation at Bolinas is correlated with the type section on the basis of lithologic and faunal similarity, although the Bolinas section is only one-tenth as thick as the type section. Martin (1916) concludes that "the Merced of Bolinas Bay... (and) of Seven Mile Beach...are... of the same age", that is, younger than the Etchegoin of the Sargent oil field and older than his "upper Merced", which he concludes is Pleistocene in age. The Merced beds at Bolinas are, therefore, middle to upper Pliocene in age, according to Martin.

The fossil marine invertebrates recorded by Martin (1916, p. 230) from Bolinas, including the most characteristic, occur in the Merced Formation at the type locality and show the close connection between the two sections. A list of fossils from these beds, including those listed by Martin (1916) and those recorded by the writer and other workers, is presented in table 6. In addition, sponge spicules, radiolaria, fish and plant remains, carbonized wood, and molds of diatoms are common.

Table 6. Fossils from the Merced Formation at Bolinas.

Crustaceans
Cancer magister Dana

Echinoderms
Scutellaster interlineatus (Stimpson)
Dendraster excentricus (Eschscholz)

Bivalves
Cardium meekianum Gabb
Cryptomya californica (Conrad)
Macoma affinis (Nomland)
Macoma inquinata Deshayes
Macoma nasuta Conrad
Macoma yoldiformis
Modiolus rectus Conrad
Mya arenaria
Paphia tenerrima Carpenter
Schizothaerus nuttalli Conrad
Solen sicarius Gould
Spisula catillifornia Conrad
Spisula hemphilli Dall

Gastropods
Astyris richtofeni Gabb
Borsonia sp.
Columbella sp.
Drillia mercedensis Martin
Eptonium indianorum Carpenter
Nassarius cooperi (Forbes)
Nassarius mendica (Gould)
Nassarius moranianus (Martin)
Neptunea sp.
Natica clausa Broderip and Sowerby

Olivella biplicata Sowenby
Olivella intorta Carpenter
Polinices cf. *P Lewissi* Gould
Thais lamellosa Gmelin

Foraminifers
Bolivina sp. (serrate form)
Buliminella dubia Barbat and Johnson
Buliminella elegantissima (d'Orbigny)
Cassidulina laticamerata Voloshinova
Cibicides sp.
Cyclammina cancellata
Elphidiella hannai (Cushman and Grant)
Elphidiella hughesi (Cushman and Grant)
Elphidiella hughesi var. *Tumida*
Elphidium granulosum
Eponides exigua
Eponides hannai
Eponides ornata
Globigerina sp.
Nonion belridgensis
Nonion scapha
Nonionella cushmani R.E. and K.C. Stewart
Nonionella miocenica var. *stella* Cushman and Moyer
Virgulina cf. *nodosa* R.E. and K.C. Stewart

Quaternary Rocks

PLEISTOCENE

Millerton Formation

These fossiliferous sand, clay, and gravel beds were named and described by Dickerson (1922) as the Millerton and Tomales Formations. Subsequently Mason (1934) and Weaver (1949) also described the beds; each of these authors thought Dickerson's two formations should be combined. Mason called the combined formations the Tomales Formation, and Weaver called them the Millerton Formation. The term Millerton Formation, following the U.S. Geological Survey nomenclature, will be used in this report.

Areal Distribution

The Millerton Formation consists of discontinuous marine and nonmarine deposits, found on headlands on the northeast shore of Tomales Bay, entirely confined to the San Andreas fault zone. It is analogous in setting to the Olema Creek Formation near Olema and to the Merced Formation near Bolinas. Since only remnants of the formation are to be found, it is difficult to determine the original form except that it is clearly related to the fault zone. It was probably laid down in an inlet similar to the present Tomales Bay.

Patches of the Millerton Formation are to be seen at Millerton Point (opposite Inverness), the point 1-1/2 miles northwest of Millerton Point, 2 miles south of the town of Hamlet, and at Tom's Point. Hog Island, in the middle of Tomales Bay near White Gulch, consists of Franciscan graywacke overlain by 10 to 30 feet of incoherent tan sand, which may belong to the Millerton Formation but which has yielded no fossils. All of these patches of sediment are, in general, similar in lithology but cannot be correlated in detail.

Lithology

The Millerton Formation includes both marine and fresh-water clays, silts, sands, gravels, and conglomerates (Johnson, 1962) which are generally deeply weathered and poorly consolidated. These beds are not continuous over any great distance, and they cannot be correlated in detail between the different exposures.

Stratigraphy

The formation is very thin as would be expected from what is probably an old terrace deposit. The maximum thickness is about 60 feet. The Millerton Formation was deposited in an environment not unlike that of Tomales Bay today, judging by the presence of both fresh-water and marine beds. According to Dickerson (1922), the fossil invertebrate marine fauna lived in warmer water than that of the present Tomales Bay and could be compared with molluscan fauna living today in the latitude of San Diego. The fossil floral evidence indicates a foggy climate very similar to the present climate at Tomales Bay. The two determinations are not necessarily contradictory, since the range of climatic conditions in the fog belt between Tomales Bay and San Diego is not very great. The invertebrate marine fauna may have lived in a warm enclosed bay, while a fog-belt climate like that of Tomales Bay today prevailed above water level.

The Millerton Formation is overlain only by alluvium and terrace deposits. Where the base can be seen, it is lying unconformably on rocks of the Franciscan Formation.

The Millerton Formation is very fossiliferous. Johnson's (1962) faunal list is included as table 7, and Mason's (1934) list is included as table 8. The same fauna and flora are found throughout the formation, and they indicate a Pleistocene age for the formation. Axelrod (1967, p. 121) mentions that the "Tomales" formation, in the sense used by Mason (1934), has been dated by the C—14 method as about 30,000 years old, while Richards and Thurber (1966) have dated the "Millerton" beds in the sense used by Dickerson (1922) as most probably more than 50,000 years old. This evidence suggests that these beds are of late Pleistocene age, and they probably can be correlated with the Olema Creek Formation.

Table 7. Fossil fauna of the Millerton Formation (Johnson, 1962).

Pelecypods
Cardium (?) sp. indet.
Chione cf. *C undatella* (Sowerby, 1835)
Compsomyax subdiaphana (Carpenter, 1864)
Corbula porcella (Dall, 1916)
Cryptomya californica (Conrad, 1837)
Glycymeris septentrionalis (Middendorff, 1849) (?)
Leptopecten latiauratus (Conrad, 1837)
Lucina nuttalli (Conrad, 1837)
Lucinoma annulata (Reeve, 1850)

Lyensia californica Conrad, 1837
Macoma nasuta (Conrad, 1837)
Mytilus californianus Conrad, 1837
Nuculana penderi (Dall and Bartsch, 1910)
N. taphria (Dall, 1897)
Ostrea lurida Carpenter, 1864
Pododesmus macroschisma (Deshayes, 1839)
Protothaca laciniata (Carpenter, 1864)
P staminea (Conrad, 1837)
P tenerrima (Carpenter, 1856)
Schizothaerus nuttalli (Conrad, 1837)
Tagelus californianus (Conrad, 1837)
Trachycardium quadragenarium (Conrad, 1837)

Gastropods
Acanthina spirata (Blainville, 1832)
Bittium eschrichtii var. *montereyense* Bartsch, 1907
Calliostoma tricolor Gabb, 1865
Cerithidea californica (Haldeman, 1840)
Crepidula norrisiarum Williamson, I 905
C. onyx Sowerby, 1824
Diodora cf. *D. murina* (Carpenter, 1885)
Epitonium cf. *E. tinctum* (Carpenter, 1864)
Littorina scutulata Gould, 1849
Mitrella gausapata (Gould, 1851)
Nassarius cf. *N. ddosi* Woodring, 1946
N fossatus (Gould, 1849)
N mendicus (Gould, 1849)
N mendicus var. *cooperi* (Forbes, 1850)
Ocenebra lurida Middendorff, 1848
Odostomia farallonensis Dall and Bartsch, 1909 (?)
Olivella baetica Carpenter, 1864
O. biplicata (Sowerby, 1825)
Phasianella pulloides Carpenter, 1 864(?)
Polinices reclusianus (Deshayes, 1839)
Purpura festiva (Hinds, 1844)
Turcica caffea Gabb, 1865

Scaphapods
Dentalium neohexagonum Sharp and Pilsbry, 1897

Arthropods
Brachyuran sp. indet.
Cirripede sp. indet.

Table 8. Fossil flora of the Millerton Formation (Mason, 1934).

Acer macrophyllum
Adenostoma fasciculatum

Alnus rubra
Amelanchier alnifolia
Arbutus menziesii
Arceuthobium cf. *campylopodum*
Arctostaphylos uva—ursi
Arctostaphylos columbiana (?)
Atriplex hastata
Baccharis pilularis
Calandrinia caulescens
Camassia leichtlinii
Carex spp.
Ceanothus rigidus
Ceanothus thyrsiflorus
Cornus californica
Corylus rostrata var. *californica*
Cupressus goveniana
Datisca glomerata
Daucus pusillus
Eriophyllum artemisiaefolium
Fomes applanatus
Fragaris californica
Galium californicum
Garrya elliptica
Montia fontana
Montia howdlii
Montia peffoliata
Montia siberica
Myrica californica
Oenanthe sarmentosa
Photinia arbutifolia
Picea sitchensis
Pinus muricata
Pinus radiata
Prunus emarginata
Prunus subcordata
Pseudotsuga taxifolia
Pteris aquilina
Quercus agrifolia
Rhus diversiloba
Rubus parviflorus
Rubus spectabilis
Rubus vitifolius
Rumex occidentalis
Rumex salicifolius
Ruppia maritima
Salix sp.
Sambucus glauca
Scirpus sp.
Symphoricarpos albus
Torreya californica

Umbellularia californica
Vaccinum ovatum

Olema Creek Formation

The name Olema Creek Formation has been given to previously unrecognized siltstone and claystone beds which crop out in Olema Creek between the Boyd Stewart Ranch and the Vedanta retreat. This outcrop has been designated as the type section.

Areal Distribution

The Olema Creek Formation is of limited distribution, being confined to the central part of the San Andreas fault zone between Five Brooks and Olema. North of Olema, if it is present, it is concealed by terrace material or alluvium. A fresh-water type, blue-grey silty clay has been observed underlying the fluvial terrace on which the town of Point Reyes Station is situated. It is not known whether the occurrence represents the Olema Creek Formation.

This formation does not extend east of the "east boundary fault" of the San Andreas fault zone, nor is it found west of the 1906 fault trace. Since the beds are soft and incompetent, there is no topographic expression, and outcrops are limited to stream banks and road cuts.

Lithology

The Olema Creek Formation consists chiefly of light blue-grey, thinly bedded and laminated clayey siltstone or claystone interbedded with coarse granitic gravel. Layers of silt and peat occur irregularly, and organic material is abundant throughout the formation (photos 17 and 18). The siltstone is dark brownish-grey and often micaceous, and the whole is somewhat current-bedded.

Photo 18. The blocky siltsones (Olema Creek Formation) near Olema contain fresh-water diatoms.

Stratigraphy

The base of the formation is not exposed, and the total thickness preserved is not known. The thickness exposed is on the order of 700 feet, based on the outcrops which dip generally westward or northward at angles up to 45 degrees.

A number of tree trunks (one in growing position) and much woody and peaty material have been found in the Olema Creek Formation. The formation also contains numerous fresh-water diatoms. The granitic gravel in the beds indicates that part of the material came from the west. It can be concluded that it was laid down in a fresh-water lake occupying part of the fault zone between Five Brooks and Olema.

It can be inferred from field relationships that the Olema Creek Formation lies unconformably on the serpentine and related Franciscan rocks of the San Andreas fault zone. It is overlain by Quaternary alluvium and stream terrace material. To the east, it is probably in fault contact with the Franciscan graywackes of the mainland. On the west, it appears to terminate against the serpentine phase of the Franciscan of the fault zone.

No definite age can be determined for the beds of the Olema Creek Formation from their geological relationships, except that they are younger than Franciscan rocks and older than the stream terraces of the Olema Valley. A C—14 measurement on the fossil wood resulted in a determination that the wood is 38,700 years old ± 2000 years. This was confirmed by an independent determination of 38,000 years.

The fresh-water diatoms present in the formation are all Holocene species, indicating that the beds are relatively quite young. Their appearance and lithification also suggests that they are quite young. The only evidence suggesting that they might be older than, perhaps, Pleistocene is that they have been tilted by earth movements which have resulted in dips as great as 45 degrees. However, the fact that they are situated in the middle of the San Andreas fault zone makes such attitudes compatible with a Pleistocene age.

A list of diatoms from these beds identified by Hanna is shown in table 9. Some of the species of fresh-water diatoms found in these beds are illustrated in photo 19. According to Hanna (per sonal communication):

"The identifications given were made with the aid of older publications. It may be that same of these names may hove been changed in later works. Many fresh-water species of diatoms are nearly world-wide in their distribution and the nomenclature has suffered because of variation. One genus contains several thousand names of species. However, in spite of this situation it is possible to make good use of them as fossils. For instance, the lake in which the species of the present study lived was a normal non-alkaline body of water. The age of deposits of the fresh-water diatoms in the for west has not been well worked out but it can be stated with assurance that in this case the age is not older than Pliocene and may well be as late as Pleistocene."

Table 9. Fresh—water species of diatoms found in the Olema Creek Formation at locality 38377 (CAS) = 41988 (CAS). See photo 19.

Cacconeis lineata Ehrenberg
Cyclotella antiqua W. Smith
Gyclotella, sp.
Cymatopleura elliptica W. Smith
Cymbella, 4 species
Epithemia turgida Kutzing
Epithemia granulata Kutzing
Epithemia zebra Kutzing
Eunotia major Rabonhorst
Eunotia, sp.
Fragilaria construens Grunow
Gomphonema, 3 species
Gyrosigma, sp.
Melosira granulata Ehrenberg
Melosira, sp. (Very large)
Navicula, 5 species
Navicula smithii Brebisson
Pinnularia americana Ehrenberg
Pinnularia dactylus Kutzing
Rhopalodia gibba (Kutzing)

Stauroneis phoenacenteron Ehrenberg
Surirella ovalis Kutzing
Tabellaria fenestrata Kutzing
Tetracyclus lacustris Balfs

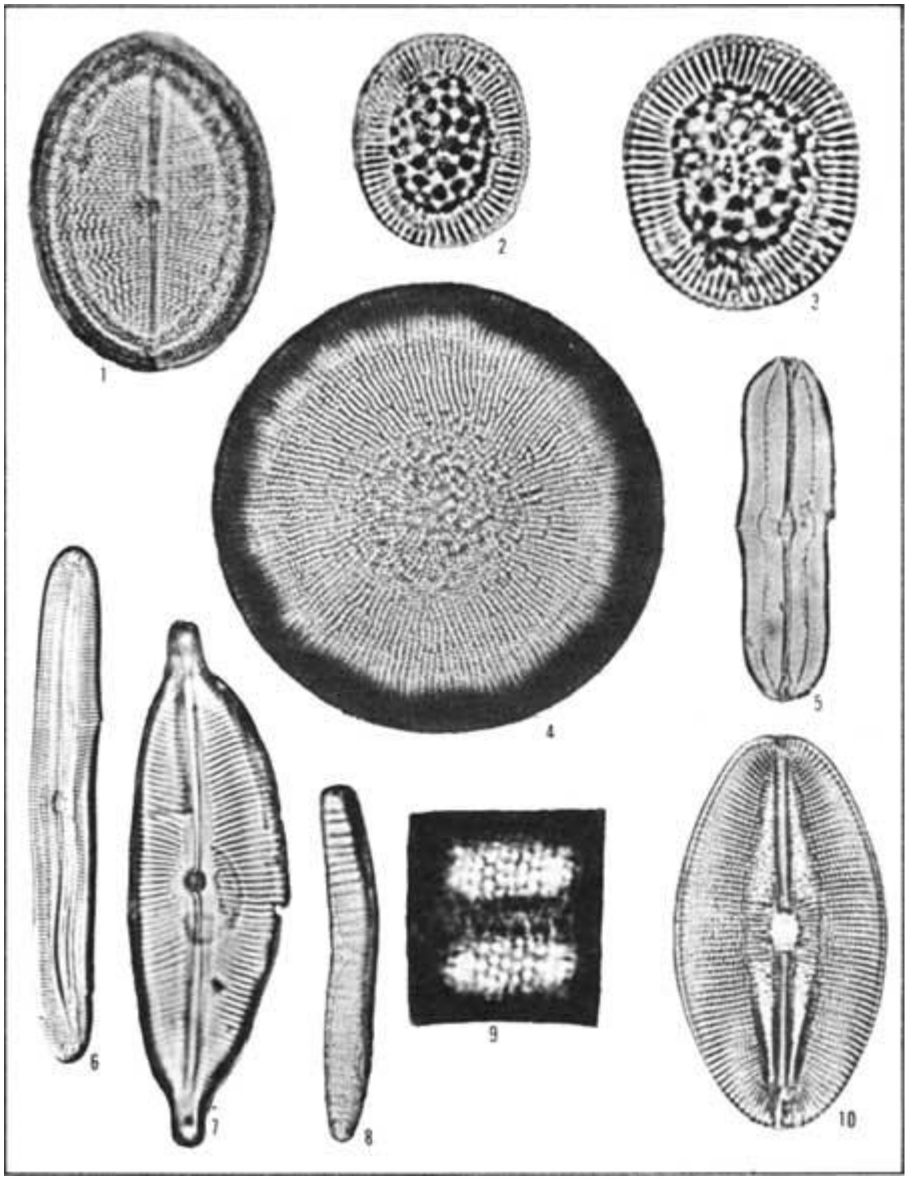


Photo 19. Diatoms from the Olema Creek Formation, All of the species illustrated in this photo are from locality 38377 (CAS) = 41988 (CAS), Truttman Ranch, Olema Creek, Marin County, California. The specimens are deposited in the collection of type materials of the Department of Geology, California Academy of Sciences, and bear numbers 20068—20077, Field No. L 603. Figure 1—*Cocconeis lineata* Ehrenberg; figures 2, 3—*Cyclotella* sp.; figure 4—*Melosira* sp.; figure 5—*Pinnularia americana* Ehrenberg; figure 6—*Pinnularia dactylus* Kutzing; figure 7—*Cymbella ehrenbergii* Kutzing; figure 8—*Epithemia granulata* Kutzing; figure 9—*Melosira* sp.; figure 10—*Novicula smithii* Brebisson, *Photos by G. D. Hanna.*

Fresh-water deposits occur at the base and at the top of the Pleistocene Millerton Formation (Mason, 1934) on the east side of Tomales Bay, about 6 miles northwest of Olema in the San Andreas fault zone. Possibly the Olema Creek Formation is correlative with these beds. The age of the Millerton Formation has been determined as probably greater than 50,000 years by Richards and Thurber (1966), but it is worth noting that C—14. age determinations on shell fragments from this formation yielded ages of 34,500 ± 3000 years and > 37,000 years in the two instances reported, thus being about the same age as the fossil wood from the Olema Creek Formation. It is concluded that the Olema Creek Formation is Pleistocene in age and probably contemporaneous, at least in part, with the Millerton Formation.

Terrace Deposits

Marine Terraces

One of the most striking features of the Point Reyes Peninsula is the prominent marine terrace which extends from Bolinas to Limantour Estero (photo 20). It is interrupted by the big landslide at the Lake Ranch between Palomarin and Bear Valley, but there can be little doubt that it originally extended continuously the whole distance. For most of its extent, it consists of a flat-topped terrestrial deposit of Monterey Shale fragments lying on top of an uplifted flat wave-cut platform formed in Monterey Shale.

Photo 20. The Bolinas-Drakes Bay terrace at the mouth of Bear Valley. This marine terrace, which extends from Bolinas to Limantour Estero, is an uplifted flat wave-cut platform in Monterey Shale.

At the south end of the peninsula in the vicinity of Bolinas, there is no terrace deposit on the broad, old wave-cut platform, called the Mesa, which is at an elevation of 120 to 200 feet. A few miles to the north, a thin non-marine terrace deposit is present on top of the wave-cut platform and the deposit thickens northward irregularly until at the U—Ranch it is nearly 100 feet thick. This non-marine deposit consists almost entirely of unsorted fragments of Monterey Shale and chert. It displays strong internal unconformities, suggesting intermittent deposition. At its base, what appears to be a thin soil (a few feet thick) and some well rounded pebbles can occasionally be seen. In this report, the terrace will be called informally the Bolinas—Drakes Bay terrace.

The upper surface of the terrace deposit remains fairly level at an elevation of 100 to 120 feet between Bear Valley and the U—Ranch; but the wave-cut platform of Miocene shale on which it rests loses elevation northward until at the U—Ranch it descends to sea level and disappears under the Holocene beach. The cliff here consists entirely of terrace material, showing that the terrace deposit thickens northward as the wave-cut platform on which it rests decreases in elevation. In Drakes Bay proper, the terrace deposit is absent.

Durst (1915) was unable to find evidence to correlate the Bolinas—Drakes Bay terrace described above with those he studied between Santa Cruz and San Francisco. Nevertheless the similarity in appearance of the Bolinas—Drakes Bay terrace to those farther south suggests that they may be of about the same age. Bradley and Addicott (1968) considered the age of the first marine terrace near Santa Cruz to be between 68,000 and 100,000 years. Hoskins (1957) concluded that the low terrace from Halfmoon Bay south was 70,000 to 90,000 years old. So it seems likely that the age of the Bolinas—Drakes Bay terrace is roughly the same as these; namely 70,000 to 100,000 years. Vestiges of probable wave-cut terraces, apparently devoid of deposits, are also seen in the hills facing the ocean behind the Palomarin Ranch, at various elevations higher than the dominant Bolinas— Drakes Bay terrace. These terraces are mentioned by Douglas and Rhoades (1915). The top surface of Tomales Point at an elevation of 400 feet is also markedly flat north of the Upper Pierce Ranch, suggesting marine planation.

The land between the U—Ranch, Point Reyes, and Abbotts Lagoon, underlain by the Drakes Bay Formation, displays a remarkably smooth upper surface (photo 21) which has been dissected by numerous valleys that originally contained streams flowing into Drakes Estero. This surface can be observed from the Point Reyes Lighthouse road a few miles north of the lighthouse.

Photo 21. Terraced surface north of Drakes Bay, with Point Reyes promontory and Drakes and Limantour Esteros in center background. *Photo courtesy of Aero Photographers, Sausalito.*

At first sight the land surface seems very similar to the Bolinas—Drakes Bay terrace in appearance and elevation, but it must be significantly older, since the north extremity of the Bolinas—Drakes Bay terrace dips under the present beach just west of the U—Ranch. Therefore, the Bolinas—Drakes Bay terrace is lower and younger than the flat surface on top of the nearby hills. This latter surface is gently warped by the Mendoza anticline and syncline and may be warped by the Point Reyes syncline, although the evidence for this is less clear. Is this flat surface a wave-cut platform or an old land surface? Minard (1964, p. 29) reported older marine terrace sands and gravels as cappings on some of the low hills (200 to 300 feet high) east of the southern part of Point Reyes Beach. These localities are west of Creamery Bay and Barries Bay. Lawson (1894, p. 245) also reported a marine terrace in this vicinity, at an elevation of about 300 to 330 feet. These observers, therefore, suggest a marine origin for this distinctive surface, although it seems quite plausible that it repreents an old low-relief land surface formed at a period of high sea level.

Stream Terraces

The open, flat central portion of Bear Valley between elevations 280 to 360 feet is occupied by an old alluvial or terrace deposit which slopes to the south. Drainage from the south end of this area flows south to the Pacific Ocean. The north end of the deposit is being eroded by the headwaters of an aggressive north-flowing stream which empties into the Olema Valley west of Olema. The deposit is largely composed of Monterey Shale fragments.

Another deposit very similar to the Bear Valley terrace or alluvial deposit is on the southeast flank of hill 1043, 10,500 feet due south of the bench mark on the summit of Mt. Wittenburg. This deposit is at an elevation of nearly 800 feet above sea level and has been considerably eroded by the headwaters of an active stream which flows south into the ocean at the Pig Ranch. This deposit, composed largely of Monterey Shale debris, must represent the alluviated floor of an old valley which has now been almost entirely destroyed by erosion. Both of these alluvial deposits belong to a cycle of erosion much older than the present. The aggressive streams which are eroding back into Inverness Ridge from both sides, approximately at right angles to the ridge; belong to the present erosional cycle. The Bear Valley deposit and the deposit at hill 1043 belong to an earlier erosional cycle, which was much more mature than the present one. The same earlier erosional cycle probably formed the mature rounded contours which prevail at the top of Inverness Ridge. It is worth noting that this older portion of Bear Valley has a nearly north-south alignment in contrast to the northeast-southwest alignment of the more recent streams.

Numerous terrace deposits are found in the long, straight valley which is occupied by the San Andreas fault zone. Some terrace deposits near Bolinas have been described by Higgins (1961) and by Gluskoter (1962). The latter refers to them as older alluvial deposits. These deposits rest on the Merced Formation which occupies the fault zone and also on the Franciscan graywacke of the mainland to the east of the fault zone. They consist of poorly consolidated coarse sandstones, gravels, and conglomerates composed of Franciscan Formation and Monterey Shale debris, and are very similar in character to the recent valley fill of the existing small valleys which enter Bolinas Lagoon and the fault zone from the east. They have been deformed to some extent by earth movement in the fault zone, showing easterly dips up to 15 degrees where exposed in road cuts at the head of Bolinas Lagoon (photo 22).

Photo 22. Older alluvial deposits exposed in a road cut near the north end of Bolinas Lagoon.

Other stream terrace deposits are found in the vicinity of the National Seashore Headquarters, previously the old Bear Valley Ranch or Skinner's Ranch (Gilbert, 1908). Between the Headquarters buildings and the forest-covered Monterey Shale outcrop to the west is a conspicuous flat terrace at an elevation of 120 to 160 feet, on which the ranch residence was built. The terrace appears to be associated with Bear Valley Creek, which debouches from the hills just south of this terrace. The southern part of this terrace deposit consists mostly of fragments of Monterey Shale. The northern part of the terrace contains a large proportion of granitic material, reflecting the exposure of the granitic basement to the north.

To the southeast of the mouth of Bear Valley Creek, a corresponding portion of terrace deposit survives at the same elevation. This portion has been affected by a branch of the San Andreas fault, which heads through it in a northwesterly direction. The terrace is underlain by faulted slivers of Franciscan Formation and of Monterey Shale. The deposit is composed largely of Monterey Shale fragments, but granitic material appears anomalously at its northern termination. Weaver (1949) correlates these deposits tentatively with the Pleistocene Montezuma Formation of the Coast Ranges, but there seems little basis for, or benefit in, this long-distance correlation.

Remains of old terrace deposits are found at a number of the higher points of Inverness Ridge where traces of an older, more mature topography are preserved. One of the most striking of these deposits is at the crest of Pablo Point, about 5000 feet west of Woodville in the Bolinas quadrangle, at an elevation of about 900 feet. Here are found cobbles of hard Franciscan chert and also of granitic rocks, apparently the hardest remnants of a nearly eroded terrace deposit resting on a surface of Monterey Shale. Similar boulders, cobbles, and pebbles are found on the southerly slopes of Stewart Point (Douglas and Rhoades, 1915).

To be in their present position, the Franciscan chert of these rocks must have been derived from the mainland east of the San Andreas fault zone. This implies that the mainland, at some post-Monterey time, must have been higher in elevation than the Point Reyes Peninsula and that the Olema—Bolinas valley was not yet eroded. Since the late Pliocene Merced Formation was apparently deposited within the fault zone depression after the valley was eroded, the deposits of which these boulders are remnants must be post-Monterey and pre-Merced in age, or early Pliocene. It is possible, therefore, that the original deposits were as old as the Drakes Bay Formation, which was then much more widespread than its present outcrop area. Rounded pebbles are also found high on Inverness Ridge at Mount Vision, and deeply weathered granitic boulders are found on Mt. Wittenburg (elevation 1400 feet). No doubt all of these occurrences are related to the period of formations of the mature topography which existed before the peninsula was incised by the present streams.

Boulders at Clam Patch

The Clam Patch is a portion of the Holocene wave-cut platform in the Monterey Shale at Bolinas which is dry at lowest tides. This area of beach, about 2000 feet southwest of the Coast Guard Mast, is much enjoyed at low tides by clam diggers; at high tides the surfboard enthusiasts take advantage of the ocean swell which breaks far out on the shallow Clam Patch.

Concealed by the waves except at low tides are numerous large, rounded boulders lying on the wave-cut platform. Some boulders are composed of the underlying Monterey Shale, but many consist of hard sandstone, conglomerate, calcareous sandstone, and occasional granitic rocks, each with a red-stained exterior. These boulders are scattered over the Clam Patch surface at random (photo 23); a few are found on the beach in the direction of Duxbury Point. Similar boulders are seen in a raised beach deposit near the top of the Bolinas cliff about 2500 feet southwest of the Coast Guard Mast. This raised beach deposit consists largely of poorly sorted yellow and iron-stained sands enclosing large boulders of various hard rocks showing a reddish "rind", or cortex, like those at the Clam Patch. Similar boulders are scattered over the east side of the Bolinas Mesa, an old wave-cut platform in Monterey Shale, now standing at an elevation of 120 to 200 feet, part of the Bolinas—Drakes Bay marine terrace. In the hills to the north, red-coated pebbles and cobbles of similar material are found on the Texeira Ranch west of the ranch house on the surface of the Monterey Shale.

Photo 23. The Clam Patch near Bolinas (1906). The exotic boulders rest on the wave-cut surface of Monterey Shale. *Photo by G. K. Gilbert, reproduced by permission of Carnegie Institution of Washington.*

It is easy to conclude that the red-stained boulders of the Clam Patch came from the old wave-cut platform of the Bolinas Mesa as the cliffs were eroded back by the ocean. But how did they reach that position?

Since no granitic rocks are now exposed closer than Mt. Wittenburg, it is necessary to assume that the granitic boulders came from there, from Point Reyes, or from some former outcrop west of the fault zone now covered by the ocean.

Some of the boulders of the Clam Patch resemble a Pliocene calcareous sandstone exposed at hill 1034 (6000 feet north of the west end of Bear Valley); possibly, therefore, the Clam Patch boulders indicate that the Pliocene Drakes Bay Formation originally extended as far south as Bolinas, which certainly seems probable judging by its present distribution.

Older Beach Deposits

East of the present Point Reyes Beach, there is a long stretch of older beach deposits which are essentially horizontal, composed of reddish-brown sand with occasional white shale pebbles, and attain a maximum thickness of about 100 feet (photo 24). These deposits crop out discontinuously in the sea cliff all the way from west Point Reyes to McClures Beach. Locally they are covered by blown sand. These beds are referred to briefly by Anderson (1899), and in more detail by Cherry (1964), Minard (1964), and Cooper (1967). Minard refers to them as "older, ferruginously cemented dune sands," but the writer agrees with Cooper that they are not dune sands but are essentially beach sands.

Photo 24. Older beach deposits east of Point Reyes Beach. These beds are essentially horizontal, are composed of reddish brown sand with occasional white shale pebbles, and attain a maximum thickness of about 100 feet.

According to Minard, these older beach deposits are derived from the Franciscan Formation and are associated with an earlier cycle of erosion and deposition. The beds have been affected by earth movement, being structurally low at Abbotts Lagoon where they cross the Point Reyes syncline, and also low west of the Mendoza ranch which lies in the Mendoza syncline. They gradually rise toward the west end of Point Reyes until they show a thickness of more than 60 feet; but, instead of extending over the top of the Point, they terminate abruptly against an old cliff facing northwest on the north side of the west end of the point. North of McClures Beach, they reach an elevation of 200 feet (photo 25).

Photo 25. Older beach deposits on the granitic surface north of McClures Beach.

Sand Dunes

The land immediately east of the 12-mile-long west-facing Point Reyes Beach is occupied by a belt of sand dunes which has been described by Cooper (1967). The outline of these dunes shown on plate 1 was delineated by the U.S. Geological Survey in 1952 when the Drakes Bay 7-1/2—minute quadrangle was surveyed. A field check suggests that there has been little change in outline since that time.

According to Cooper (1967, p. 40), the main belt of dunes "is made up of scores of overlapping tongues and narrow parabolas pointing southeast." One interesting long tongue crosses the highway near Bench Mark 166 at about the latitude of the D— Ranch. Another tongue, strikingly illustrating the persistance of the prevailing northwesterly wind, has climbed from the beach up the north-facing slope of western Point Reyes and crosses the lighthouse road not far from the RCA radio tower. This tongue is not shown on the geological map, since its thickness is not great. East of the belt of dunes in the area north of the RCA installation, the soil is concealed under a thin layer of blown sand for a considerable distance inland.

STRUCTURE

San Andreas Fault

The San Andreas fault zone, forming the long straight inlet of Tomales Bay and the long straight valley between Olema and Bolinas Lagoon, is overwhelmingly the most important structural and physiographic feature of the Point Reyes Peninsula.

In order to avoid confusion, in this report the words "San Andreas fault zone" are used in the sense employed by Noble (1926) to designate the band of roughly parallel fractures which accompany the "fault trace," or master-fault. The words "1906 fault trace" are used to designate the actual break in the ground which occurred at the time of the San Francisco earthquake of April 18, 1906. This 1906 fault trace lies wholly within the "San Andreas fault zone." The term "rift," used by Lawson (1908) to designate the belt of topographic features along the fault zone, will not be used in this report.

Quoting Crowell (1962), it can be truly said that, in the section between Bolinas Lagoon and Tomales Bay, the fault zone "consists almost everywhere of a broad shallow trough filled with fault land forms, such as scarps, slice ridges, sag ponds, shutterridges and offset streams." Driving along State Highway 1, these topographic features are visible from the road. In particular the passer-by will notice the slice ridges near the Hagmaier Ranch, the big sag pond east of State Highway 1 about a mile north-northwest of Five Brooks and the shutterridges along the 1906 fault trace near the National Park Headquarters. At Bolinas Lagoon and Tomales Bay, the trough of the fault zone has been invaded by the ocean. Sharp (1954) described seventeen primary fault features and seven secondary fault features in southern California, and most of these physiographic features also can be seen here.

The fault zone is distinguished not only by the land forms but also by the fact that the Franciscan rocks, which to the east consist almost entirely of graywacke, within the fault zone consist mostly of serpentine, pyroxenite, decomposed ultrabasic rocks, and other rock slices and boulders, termed "tectonic inclusions" by Schlocker and Bonilla (1962), which are demonstrably not in place and which have presumably been moved along the fault zone. The Calera limestone block near Five Brooks is an example. Many of these stand as isolated boulders in the grassy meadows.

The Franciscan of the fault zone is overlain by the marine Merced Formation at the southeast end of the zone and by the fresh-water Olema Creek Formation at the northwest end. In the vicinity of Five Brooks this serpentine-bearing phase of the Franciscan Formation is exposed at the surface. The fault zone in this area seems to be bounded by two large fault traces, one on each margin, termed the east and west boundary faults for convenience. The nearly parallel sides of the long narrow inlet of Tomales Bay suggest that it too is bounded by two parallel faults.

The east boundary fault trace is distinguished by many sag ponds and strong topographic evidence of a large fault east of State Highway 1, northwest from Five Brooks. The topographic expression of this fault here is greater than along the 1906 fault trace, suggesting that movements on the east boundary fault have been large and frequent in the not too distant past. This fault seems to disappear under terrace deposits to the northwest and the southeast, but no doubt it is represented by the east side of Tomales Bay.

To the south, it seems likely that the continuation of this fault determines the position of the east side of Bolinas Lagoon. The occurrence of hot springs on the beach just north of Rocky Point suggests that the faulting may extend as far south as that locality. Tectonic inclusions can be seen beside State Highway 1 near here.

Another large fault seems to form the west boundary of the San Andreas fault zone. This fault, also marked by striking topographic features, has a more pronounced effect on the geology since it separates Monterey Shale and granitic basement in the north from the Franciscan of the fault zone. The west boundary fault trace is occupied by Paradise Valley near Bolinas; further northwest, it is occupied by the upper portion of Pine Gulch Creek.

Northwest of Pine Gulch Creek, the west boundary fault appears to control Olema Creek on the west side of the peculiar rhomboidal detour it makes in its course just south of Five Brooks. Three thousand feet northwest of Five Brooks, it seems to coincide with the 1906 trace and then diverges at a small angle to the west of the 1906 trace until at Olema it is nearly 2000 feet west of it. Northwest of this point, its course is obscured by terrace deposits, but it is no doubt represented in a general way by the granitic margin of the west side of Tomales Bay. This west boundary fault was observed in the Bolinas sea cliff in 1913 (Bradley, 1915, p. 243) as a vertical fault. Projecting it southeastward, it is intriguing to imagine it connecting with the Pilarcitos fault (San Mateo county), which lies in a similar geological environment with the granitic Montara Mountain to the west, and the Pliocene Merced Formation to the east, underlain by Franciscan rock. It might also be speculated that the San Bruno fault corresponds to the east boundary fault of the Olema Valley (see San Franciscan sheet, Geologic Map of California).

Many additional fault traces are found in the fault zone and show topographic expression. The most clearly marked is, of course, the most recent—the rupture caused by the 1906 earthquake. This is described in fascinating detail by Gilbert (1908), and students of the area can be grateful that this eminent and thorough geologist was available to describe the Point Reyes Peninsula section of the rupture in the classic report of the California Earthquake Investigation Commission. Gilbert's descriptions are so clear that it is easily possible over sixty years later to retrace his footsteps in spite of the growth of vegetation and changes in cultivation and houses.

No attempt will be made here to repeat Gilbert's work, since it could hardly be improved upon, although he had no reliable topographic map of the area. He described the surface expression of the rupture as taking three forms: the ridge phase, the trench phase, and the echelon phase; traces of the first two can still be seen. The minor surface features of the 1906 rupture are surprisingly persistent.

The 1906 rupture at Bolinas, which cut the tip of Stinson Beach sandspit, was about 3500 feet from the west boundary of the fault zone as expressed by the Merced—Monterey contact. Northward at Five Brooks the fault zone is only about 1500 feet wide, and the 1906 trace is over against the west side of the zone. Farther northward, the zone widens and forms the submerged depression of Tomales Bay. The 1906 trace is established by lying more or less centrally between the two edges of this inlet (Lawson and others, 1908). The 1906 fault trace cut Tom's Point and Sand Point (near Dillon's Beach) but apparently did not cut Millerton Point. At Bodega the 1906 trace was close to the east side of the fault zone.

Many other shorter, more discontinuous, fault traces are to be seen in the fault zone, and some are as impressive as the 1906 trace. It seems clear that the fault zone has been the locus of a very large number of earth-ruptures (accompanied no doubt by large earthquakes) over a long period of geologic time.

WIDTH AND LENGTH

Tomales Bay is about 7000 feet wide at its northern end, suggesting that the width of the fault zone there is of that order. Southward, the fault zone narrows to 1500 feet at Five Brooks, widening again southward to about 4000 feet at the head of Bolinas Lagoon, and is about 8000 feet wide at the latitude of Bolinas (assuming the east shore of Bolinas Lagoon is the east boundary of the fault zone). This width is narrow compared with the 6 mile maximum width of the fault zone in southeastern California (Noble, 1926). The total length of the segment of the San Andreas fault zone in the Point Reyes Peninsula, measured from Tomales Bluff to Bolinas, is about 30 miles.

ASSOCIATED FAULTS AND FRACTURE TRACES

It is mentioned above that many fault traces are to be recognized by their topographic expression in the fault zone itself. Outside the fault zone there are a number of dislocations that can be similarly recognized; these can be divided arbitrarily into: (1) associated faults and (2) fracture traces.

Gilbert (1908) reported a rupture of the surface which he attributed to "a divergent branch of the fault" in the north part of Bolinas, trending approximately north-south and fading out in both directions near the present site of Bolinas School (Lawson and others, 1908, p. 81). Since this rupture was in the alluvial plain, it seems equally possible, in hindsight, that it was caused by lurching of the incompetent alluvium. There seems to be no other evidence of a north-south fault in this vicinity. Several topographic expressions of fault traces traverse the Merced terrane to the north of the school, but these are all aligned in a northwesterly direction. This branch of the fault described by Gilbert would lie entirely within the fault-zone as defined above.

Gilbert also described a "bedrock crack" on Mt. Wittenburg, crossing the "northeastern spur of the peak near its junction with the main crest," and trending northwest-southeast. Aerial photographs show a sharp straight ravine, very suggestive of a fault, starting close to the National Park Headquarters in Bear Valley and heading toward the northeastern spur of Mt. Wittenburg. However, efforts to find remaining traces of this bedrock crack on the ground were unsuccessful, so this particular topographic indication should probably be referred to as a fracture trace (see below).

In addition to the above, Gilbert mentioned a "branch fault trace" about 1/2 mile long, traversing the ridge between the Second Valley and Third Valley at Inverness. Gilbert's report shows a photograph of this fault trace (plate 47A) and indistinct relics of it are to be seen on the ground today. Its geologic setting suggests that it was indeed a genuine bedrock crack, but no unequivocal indication of it is to be seen in the aerial photographs, perhaps on account of the subsequent growth of scrub and trees.

Aerial photographs disclose a band of apparent "fracture traces" (Lattman, 1958) west of the fault zone in the vicinity of Mud Lake. The fracture traces form a lineament which leaves the fault zone in a northwesterly direction and then curves concave to the fault zone until it becomes almost parallel to it. In the center of this lineament lies Mud Lake, an anomalous pond resembling a sag pond, on the top of Inverness Ridge. The lineament becomes indistinct and dies out not far north of Mud Lake.

Examination on the ground has failed to disclose the features responsible for this lineament; indications of fault topography are abundant but indistinct. The lineation could be due to bedding in the Monterey Shales; however the thickly forested area yields few measurable attitudes, and the general impression is that dips and strikes in the shales are not as regular as would be required for this explanation.

That this photogeologic lineament is a fracture trace is supported by an observation of Gilbert (1908. p. 76):

"A pond known as Mud Lake, on the divide at the head of Pine Gulch Creek and about a mile from the fault-trace, suddenly and permanently lost its water at the time of the earthquake. At the same time a small spring on the east side of the ridge and about 0.75 mile in a direct line from the pond, was suddenly enlarged, a torrent of water gushing from it for several hours and then gradually diminishing".

This occurrence could well have been due to the opening by the earthquake of some of the fractures in the vicinity of Mud Lake. Mud Lake today contains water, the 1906 crack having no doubt been filled with sediment.

Clague (1969) considers it probable that the formation of Mud Lake is involved in older landslides. This however is not incompatible with the fracture trace explanation of the photogeologic lineament described. The long lineaments on the aerial photographs are reminiscent of the faint surface lines reported by Warne (1953) in the vicinity of Bakersfield and attributed by him to minor faulting, although the forest cover on Inverness Ridge makes the features there more discontinuous to the eye than those in the San Joaquin Valley.

A drainage anomaly at the point where the lineament from Mud Lake intersects the fault-zone trough also suggests that the lineament is due to a fault or fracture trace. It is concluded that these faint lineations seen in the forest cover of the south part of Inverness Ridge are expressions of minor faulting or cracking related to movement on the San Andreas fault zone. The more prominent "fracture traces" are shown on plate 1. Evidence of faulting is sparse on the Franciscan block east of the fault zone, suggesting that these rocks may have yielded by folding instead of by faulting.

DIRECTION OF THE MOVEMENT

There is no question about the direction of the movement on the San Andreas fault in 1906. Lawson and others (1908) reported that practically all the movement in 1906 was right-lateral; that is, the ground on the southwest side of the fault moved horizontally northwest relative to that on the northeast side. Table 10 shows the 1906 displacements.

Table 10. Horizontal surface displacements in the earthquake of April 18, 1906.

Location	*Displacement*
Fence, 1.25 miles southeast of Mussel Rock (San Mateo County)	13 feet
Eucalyptus trees, 1 mile northwest of Bolinas Lagoon	13.5 feet
Fence near Bolinas Lagoon	More than 12 feet
E. R. Strain's place (now Texeira Ranch); fences	15 and 11 feet
W. D. Skinner's place (now Park Headquarters)	Average 15.25 feet
Road southwest of Point Reyes Station	20 feet

Tom's Point (reported by R. S. Holway)	8 feet
One mile southeast of Fort Ross (Sonoma County)	12-15 feet

The possibility of vertical movement in the Marin County segment of the fault trace was carefully examined by Gilbert, and he concluded that it could be demonstrated only that the part of Bolinas Lagoon east of the fault had probably subsided 12 inches relative to the part west of the fault. His photographs show that in many places the 1906 trace is bordered by what appears to be a fault scarp, but these scarps were due in part to landsliding and in part to lateral movement of slices along the fault, bringing higher ground in juxtaposition with lower ground (Gilbert's "fault ridges".) Lawson and others (1908, pl. 52A) illustrate a scarp which is actually the head of a Lake Ranch landslide. The fault ridges face indiscriminately southwest or northeast, making their origin from vertical movement unlikely. Gilbert himself saw the possibility of the "appearance of vertical displacement largely due to combination of horizontal displacement with slope of ground." Gilbert saw little convincing evidence of vertical movement on the 1906 fault trace; most California geologists today probably concur that horizontal movement is the dominant feature of the San Andreas fault zone (Dickinson and Grantz, 1968).

However, Oakeshott (1966) makes a plea for retaining a flexible position with respect to the possibility of vertical movement on the fault, and it is worthwhile looking at the regional geology with this in mind. The highest point of Inverness Ridge, lying between the fault zone and Drakes Bay, is Mt. Wittenburg (elevation 1407 feet). Mt. Wittenburg is overlain by Miocene marine sediments so Inverness Ridge has been uplifted more than 1400 feet since the Miocene. The beds on Inverness Ridge dip southwestward into the Drakes Bay syncline.

On the northeastern side of the fault zone in Marin County lies the "San Francisco—Marin fault block" (Lawson, 1914), composed mostly of Franciscan rocks. This fault block dips northeastward, in the opposite direction, and its eastern margin has been invaded by the waters of San Francisco Bay, just as the center of the Drakes Bay syncline has been invaded by the waters of the Pacific Ocean. The highest point on the San Francisco—Marin block along Bolinas Ridge bordering the Olema Valley is about 1440 feet. This means that the rocks on both sides of the San Andreas fault zone have been uplifted, forming now a kind of roof-ridge structure along the fault zone. This is compatible with the generally accepted conclusion that the San Andreas fault zone is an area of compression. Whether the uplift has taken place as vertical faulting, or otherwise, is not disclosed by the evidence. But uplift there has been in the geologic past, and enough subsequent erosion to expose the granitic pluton of the Point Reyes Peninsula at the surface.

Nevertheless, all the topographic evidence within the zone itself points to long-continued lateral (horizontal) movement. The rocks on the two sides of the zone are quite different so there is no opportunity in the area to measure the total displacement on the fault zone by comparing the two sides. However, an interesting geological detail bearing on the nature of the movement came to light during the field work for this report. The lake beds of the Olema Creek Formation contain abundant granitic material almost certainly derived from the granitic rocks of Inverness Ridge. This granitic sedimentary material extends south in Olema Creek almost as far as the Boyd Stewart Ranch. The nearest granitic outcrop today is the small inlier in Bear Valley near the old Country Club. If this inlier provided the material, it must have been transported northward to the fault zone via Bear Valley Creek, and hence will have reached the fault zone approximately at the Vedanta Retreat (formerly Shafter Ranch), about 12,500 feet along the fault zone, from the Boyd Stewart Ranch. This detrital granitic material has been displaced this distance laterally southeastward along the fault zone since it was deposited. Since long-term average annual rates of movement along the fault zone are variously estimated as between 1/2 inch and 2 inches per year, these numbers are compatible with the conclusion that the Olema Creek beds are Pleistocene in age. The Olema Creek beds lie on the northeast side of the 1906 trace, so the right-lateral movement could have taken place on this trace.

Thus, there is some evidence that right-lateral movement has been taking place here since Pleistocene time. What movement took place before that time has to be determined by correlations across the fault outside the Point Reyes Peninsula. At the present time, most students of the question feel that right-lateral movements at average rates between 1/2 and 2 inches per year have persisted since Cretaceous times (Dickinson and Grantz, 1968).

The fact that the Bolinas end of the valley, in which the San Andreas fault lies, was filled with Merced marine sediments during late Pliocene time indicates that the Olema—Bolinas valley was already eroded at that time, suggesting that the San Andreas fault zone is at least older than the Merced Formation. The remnants of terrace beds containing Franciscan material, lying on the Monterey Shale, suggest that the cutting of the Olema Valley was post Miocene. Thus the erosion of the Olema—Bolinas valley took place between late Miocene and late Pliocene time.

One argument in favor of long-continued lateral movementon the San Andreas fault can be based on the complete difference between the rocks on the two sides of the fault zone—Franciscan on the east and granitic plus Tertiary on the west. To account for this geological setting, Lawson (1914) invokes tremendous oscillating vertical movements on the San Andreas fault to ac count for the absence of the Franciscan Formation on the west side, in spite of the example of the convulsive right-lateral movement of 1906 which he himself observed.

Application of the principle of simplicity (Anderson, 1963) would lead one to prefer the hypothesis of a long-continued lateral movement, similar to that actually observed, to the hypothesis of the large vertical movements necessary to strip rocks of the Franciscan Formation from the west side and the Tertiary rocks from the east side of the fault.

SHUTTERRIDGES

The fault zone between Inverness Park and Five Brooks is distinguished by a succession of elongated ridges parallel to the 1906 trace on the northeast side of the fault zone. Gilbert (1908) called these ridges "peculiar in that their western, or more strictly southwestern, base being determined by faulting, is nearly straight; while their northeastern base, modified by the erosive action of Olema Creek, is scalloped." The ridges, as far southeast as the Truttman Ranch, are composed of granitic and Monterey Shale debris, clearly derived from Inverness Ridge; they correspond, therefore, to Buwalda's (1936) definition of shutterridges as "ridges which by fault shift, horizontally or vertically or in both components, tend to move across, block and shut in the ravines or canyons of streams crossing the fault." Bear Valley Creek and Cold Creek (5000 feet northwest of Five Brooks) have certainly been blocked by the movement of these ridges, so that the term shutterridge seems appropriate. No doubt those ridges, composed of granitic and Monterey Shale debris, were originally portions of outwash fans of streams coming from Inverness Ridge, which originally flowed across the 1906 trace from west to east. The ridges were shifted to the southeast by right-lateral movement on the northeast side of the 1906 trace.

EARTHQUAKES AND CREEP

The San Andreas fault in California is associated historically with several large earthquakes and many small ones. The Point Reyes Peninsula segment of the fault has been relatively quiet seismically since the tremendous 1906 earthquake. On segments of the fault near Hollister and Parkfield—Cholame, creeping displacement is taking place at the surface, and shallow small earthquakes are frequent.

Inspection of the 1906 trace in Marin County fails to show any tectonic creep, and if movement is taking place along some other segment in the fault zone, it has passed unobserved. This lack of creep seems to be consistent with the absence of small earthquakes along this stretch. Special efforts to locate evidence of recent fault traces have been unsuccessful.

Although progress has been made in earthquake prediction, at this time no certain method of forecasting the occurrence of earthquakes has been developed. A study of the San Andreas fault zone in Marin County convinces one that a great deal of earth movement, presumably accompanied by earthquakes, has taken place in the past. There is no reason to expect any future change in this situation, but whether the next earthquake on this segment of the fault will occur today, tomorrow, next year, or 100 years hence cannot now be determined.

STREAM DIVERSION

At the north end of Olema Valley, Bear Valley Creek emerges from the hills west of Olema and flows northeastward until it reaches the 1906 trace, where it makes an abrupt right-angle turn to the northwest. It does not cross the 1906 fault trace but continues northwestward into Lagunitas Creek at the head of Tomales Bay. It is prevented from joining Olema Creek by the shutterridges which have moved across its course.

The next stream to the south (unnamed) flows northeasterly from the hills until it reaches the fault trace of 1906, where it turns northwest for 1000 feet, after which it resumes its northeasterly course and flows into Olema Creek. The sharp turn of this stream to the northwest is apparently due to its northeasterly course having been blocked by a shutterridge.

Further southeast and still on the southwest side of the 1906 fault trace, a stream, locally known as Cold Creek, joins Olema Creek close to bench mark 167, about 3500 feet northwest of Five Brooks. The upper part of its course is northeast, but on approaching the 1906 trace it describes a wide curve to the southeast, flows southeast along the fault trace for 2000 feet, and then joins Olema Creek to flow northwest. It is as though its junction with Olema Creek had been pushed southeastward by the long shutterridge whose highest point is marked as 257 feet elevation on the topographic map (Inverness quadrangle). Other streams to the southeast of Cold Creek also show a southerly bend.

At Five Brooks, as the name implies, the drainage is very complex and is undoubtedly affected by fault movements. South of Five Brooks, the streams coming from the west do not flow into Olema Creek, which is separated from them by a series of fault-slices; instead they form the headwaters of Pine Gulch Creek which in the upper part of its course runs along the west boundary fault of the San Andreas fault zone. In this area, Olema Creek and Pine Gulch Creek run parallel to one another in opposite directions, separated only by about 1500 feet, with Olema Creek flowing into Tomales Bay to the north and Pine Gulch Creek into Bolinas Lagoon to the south.

Pine Gulch Creek, instead of going directly southeast into Bolinas Lagoon as one would expect, turns southwest through Paradise Valley and eventually empties into Bolinas Lagoon near Union School.

The writer has considered various possible causes for this behavior. The stream could perhaps have ponded and diverted through Paradise Valley by a landslide in the neighborhood of Woodville; but there is no obvious evidence of this. The same effect could have resulted from tectonic uplift in the vicinity of Woodville. No doubt the stream has been affected by fault movements, but it is difficult to see exactly what type of movement could have caused this anomaly. Higgins (1961) suggests that its anomalous course might be due to superposition from a blanket of terrace deposits.

A more likely immediate cause would seem to be stream-capture by a tributary of the actively eroding McCormick Creek. This creek presumably originally flowed from the south side of Pablo Point through Paradise Valley into Bolinas Lagoon; after the rejuvenation by the recession of the ocean which formed Bolinas Mesa, a northeasterly tributary may have cut back and captured the waters of Pine Gulch Creek, diverting them away from their course which originally led to the end of Bolinas Lagoon.

On the northeast side of the fault zone in the Olema Valley, there is little evidence of stream diversion due to fault movement.

Regional Structure

The Point Reyes Peninsula is synclinal in general form. The oldest rocks crop out on Inverness Ridge and at Point Reyes, on the northeast and southwest margins of the territory; the central synclinal part is occupied mainly by the Pliocene Drakes Bay Formation. The axis of the central syncline, termed the Point Reyes Peninsula syncline by Weaver (1949), is occupied by the drowned valley of Drakes Estero, which suggests recent sinking of this area. The Bolinas terrace extends discontinuously northwest as far as Drakes Bay, where it dips under the present beach on the east side of the syncline. The present position of the older beach deposits along Point Reyes Beach suggests recent uplift at Point Reyes and Tomales Point, with an intervening syncline.

Cores from oil well tests suggest that Point Reyes syncline thickens to the south under the ocean. This is also suggested by regional gravity anomalies (Chapman and Bishop, 1968).

Local Structure

FOLDS

An easily accessible anticlinal fold is exposed in the sea cliff about 6000 feet southwest from Drakes Beach County Park. This fold is strongly asymmetric, with southwest dips of about 40 degrees on the southwest flank and northeast dips of about 5 degrees on the northeast side. The axis trends northwest across the peninsula. Southwest of the axis, there is a shallow complementary syncline, the east end of which is clearly outlined in the offshore kelp beds (photo 26). These features are referred to in this report as the Mendoza anticline and syncline after the ranch on which they are situated.

Photo 26. The Mendoza syncline. underwater in Drakes Bay, is outlined in kelp.
Photo by Towill, Incorporated, San Francisco, and U. S. Army Corps of Engineers.

An unsuccessful exploratory oil well drilled on the axis of the Mendoza anticline encountered granitic basement at a subsea depth of about 600 feet. It seems likely that the anticline expressed in the Drakes Bay Formation reflects vertical faulting in the basement complex.

A small steep anticline involving the Monterey Shale as well as the Drakes Bay Formation extends northward from the head of Schooner Bay at the north end of Drakes Estero. At the latitude of the south end of Abbotts Lagoon, it heads into a strong anticlinal fold trending approximately east-west. The hill which divides Abbotts Lagoon into two parts seems to be a topographic expression of this east-west uplift. To the east the uplift appears to extend back into the granitic basement, causing a swing in the granitic outcrop at the Sir Francis Drake Highway.

Further to the southwest another line of folding, running more or less northwest-southeast, is expressed by inliers of Monterey Shale which appear in the outcrop of the Drakes Bay Formation at and northwest of the Home Ranch. This fold extends southeast as a steep zone as far as Glenbrook Creek, where an inlier of granitic rock is exposed in the creek bed. This or a similar steep zone extends southeast through Muddy Hollow and the Laguna Ranch, nearly to the Y—Ranch, southeast of which it disappears in the complexities of the Wildcat Ranch landslides.

A syncline in Monterey Shale is exposed on the beach about 4000 feet northwest of the mouth of Arroya Honda. The "Religious Colony slump" of Clague (1969) can be seen in the cliffs above the syncline. Northeast of the Religious Colony (Palomainn) site is a steep zone of vertical and overturned beds in the Monterey Shale, which dies out to the southeast and disappears into the Double Point landslide to the northwest.

Previous writers (Lawson, 1914; Leck, 1921; Douglas, 1943) have described an anticline parallel to the west side of Bolinas Lagoon and about 1/2 mile to the west. The present mapping did not confirm the existence of this fold. The attitudes of the incompetent Monterey Shale exposed in the cliff between Bolinas and Duxbury Point seem to be essentially vertical (judging by the layers of concretions). Near Duxbury Point the beds dip generally about 45 degrees to the southwest.

At Duxbury Point some subsurface structural complexity at depth is indicated by east-west striking beds which dip southward and by oil and gas seeps in the vicinity.

Numerous other minor folds exist, particularly in the vicinity of U—Ranch and Home Ranch. The long sinuous folds shown by Weaver (1949) are not confirmed by the present mapping, with the exception of his "Country Club anticline," which causes the small inlier of granitic basement in Bear Valley. The incompetent Monterey Shale is often so contorted, possibly by sliding down the continental slope during deposition, that small exposures are unreliable indicators of structure.

FAULTS

A textbook example of a nearly vertical fault can be seen in the cliff section due west of the Kehoe Ranch (photo 27). This reverse fault, apparently related to the uplift of Tomales Point, strikes east-west and has displaced Laird Sandstone against granitic basement. Other minor faults, too small to depict on plate 1, extend east-west across the point here, the largest lying completely in granitic rock.

Photo 27. Reverse fault in the sea cliff near Kehoe Ranch. Laird Sandstone has been displaced against granitic basement rock.

Weaver (1949) shows a northwest-southeast fault immediately south of White Gulch on Tomales Bay near its northern end. Laird Sandstone is in place on the northeast side of this fault, although eroded from most of the surrounding granitic rock. It seems very likely that such a fault is present here, but since no evidence of it was seen, other than the topography and the presence of the Laird Sandstone, the fault is not shown on plate 1. Both the topography and the presence of the Laird Sandstone could be due to an originally irregular surface of the basement rock.

The anomalous east-west alignment of the Point Reyes Ridge, with its nearly straight south-facing cliff, can best be explained by postulating the existence of an east-west fault, down-thrown to the south, under the sea just off shore. If this is correct, the Point Reyes Ridge south face is a fault-line scarp. The gravity field seems to confirm this (see "Geophysical Surveys").

The Point Reyes Ridge is broken by a number of small faults in a complex pattern. More faults exist here than are shown on the map. Some of them seem to be pre-Drakes Bay Formation in age.

Numerous small faults can be seen in the Drakes Bay Formation that forms the white cliffs of Drakes Bay; these are insignificant in displacement and are not shown on the geologic map.

GEOMORPHOLOGY

Geomorphology is the study of the shape of the land and how these shapes were formed. The general geomorphology of the area has been discussed under "Geography". Some of the interesting land forms on the peninsula are discussed below.

Fault Zone

The San Andreas fault zone is the dominating geomorphic feature of the area and has been described in the section on the San Andreas fault. Land forms typical of faulting occur all along the fault zone and these are described graphically by Lawson and others (1908, p. 29-35), with many illustrative photographs. It should be emphasized that State Highway 1 between Bolinas Lagoon and Tomales Bay is a display-case of classic fault landforms which can be easily seen from the highway.

Older Topography

Many of the upper slopes of Inverness Ridge show deeply weathered, mature rounded forms quite different from the sharp angular slopes being cut by present streams. The formation of these rounded, mature land forms dates from some earlier, more advanced cycle of erosion than the present one.

Marine Erosion

Like any tectonically active area with a long coast line, the Point Reyes Peninsula displays some dramatic examples of marine erosion. The cliffs along the sheltered waters of Tomales Bay are well protected; but, on the west side of Tomales Point and on the south facing Point Reyes promontory, stacks, rocks, and off-shore islands bear witness to the erosive power of the Pacific Ocean. Between the two points lies the long straight Point Reyes Beach, where erosion and deposition seem to be more or less in equilibrium (Cherry, 1964).

In Drakes Bay the presence of high cliffs points to the existence of substantial erosion; these cliffs are protected from the prevailing northwest wind but receive the brunt of the winter storms, characterized by gales from the south. On several headlands in Drakes Bay, a topographic high is found at or close to the coastline, indicating considerable wave erosion in the past. For instance, the southern extremity of Drakes Head (147 feet elevation) marks the mature stage of a shoreline of submergence, the cliff having been cut back as far as the landward-sloping side of a hill. The drowned valleys of Drakes Estero and Estero de Limantour are evidence that the coast has been submerged.

The eastern part of Drakes Bay is protected by a long sandspit, Limantour Spit. East and south of this area the hard, brittle Monterey shales and cherts have been greatly eroded, particularly where layers and pod-like injections of sand form relatively weak areas which the waves quickly turn into caves. The low terrace covered with land-laid deposits (elevation about 100 feet), which forms such a striking feature of the coast here, must have originally extended much farther seaward.

South of Bear Valley the terrace disappears completely and a large area of landsliding persists for several miles southward to the vicinity of Palomarin Ranch. While earthquakes and faults have probably contributed to the formation of this large complex of landslides, one of the immediate causes is the erosion of the incoherent sea cliff, which results in continuation of the sliding. Gilbert (1908) observed a change in the landslide area after the 1906 earthquake.

South of Palomarin Ranch, the amount of erosion was accurately measured by the U.S. Coast and Geodetic Survey. Since 1859 Duxbury Point has eroded about 60 meters, Bolinas Point has eroded about 50 meters, and a point 4000 feet north of Bolinas Point has eroded about 60 meters. These measurements indicate an average rate of erosion of around 2-1/2 feet per year. Along this stretch of coast from Palomarin Ranch to Duxbury Point, the Monterey mudstones are well bedded and mostly dip at about 45 degrees seaward. Thus, when the bedding planes are lubricated with rainwater or drainage water, landslides are very apt to occur at the sea cliff. Waves quickly remove the material at beach level and the whole slide remains unstable, gradually eroding back from the ocean in an effort to reach a stable angle of repose.

At Bolinas, soft sands and silts of the cliffs in the Merced Formation are sheltered from the prevailing northwest winds but face the southerly storms of winter. Here erosion has also been dramatic. A house originally built on the ocean bluff (along with its site) has entirely disappeared, while another projects over the cliff and is supported by pillars. A bulkhead, built in the 1890s at the base of the cliff, was destroyed about 1913 by winter storms. From the bulkhead remains, it was determined in 1962 that the cliff has eroded about 75 feet since 1913, an average of 1-1/2 feet per year. Erosion here, as elsewhere in the Point Reyes Peninsula, is irregular and several years often pass without any obvious recession of the cliff.

Bolinas Lagoon and Tomales Bay

These two bodies of water have the appearance of drowned valleys, and both are in the San Andreas fault zone. They occupy valleys that must have been eroded during a low stand of the sea, perhaps at the time of the Wisconsin glaciation (figure 4), after which the return of the sea to its present level flooded the parts adjacent to the ocean (photo 1). Both inlets are at present being silted up by erosional debris from the surrounding hills. The present-day streams, rejuvenated by the earlier retreat of the sea, have cut sharp V-shaped canyons in their lower courses; the effect of this can be seen in Bolinas Lagoon where Pine Gulch Creek is building a delta into the Lagoon (see "Stream Diversion").

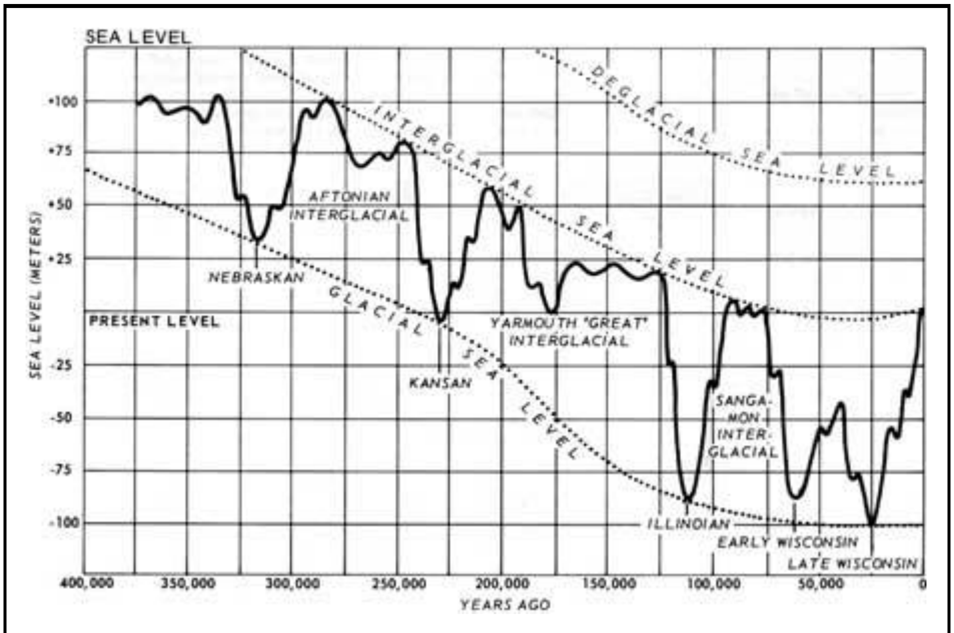


Figure 4. Variations of sea level during the Ice Age. *From Fairbridge, 1960; reprinted with permission from 'Scientific American'. (click on image for a PDF version)*

Alluviated Valleys

The long, narrow alluviated valleys of Laguna Ranch Creek, Muddy Hollow Creek, and Glenbrook Creek were originally V-shaped. The coastal outlets of these creeks have been affected by the downwarping of the Point Reyes syncline. Marshes, lagoons, and sandspits have been formed and the valleys have been partly filled with alluvium. The upper reaches of the creek valleys are steep-sided and the canyons would be distinctly V-shaped if the alluvium were removed. The alluviation of these valleys, therefore, is later than a period of vigorous erosion which cut the original V-shaped valleys (photo 28). The cutting of the valleys took place during a period of low sea level, probably during the Wisconsin glacial period; the alluviation of the valleys took place later, when the Point Reyes syncline was formed and the valleys were invaded (drowned) at their lower ends by the sea.

Photo 28. View south with Drakes Bay and Limantour Spit in the background. The long, narrow alluviated valleys of Muddy Hollow Creek (right center) and Laguna Ranch Creek (left) lie east of Drakes Estero. *Photo courtesy of Aero Photographers, Sausalito.*

Point Reyes Promontory

The area between the granitic promontory of Point Reyes and Drakes Estero is distinguished by an anomalous alignment of ridges and valleys running approximately northwest-southeast, as compared with the prevailing N.35°W. strike of the San Andreas fault and Inverness Ridge. These ridges and valleys are controlled partly by the structure of the area, the ridges being in most cases the expression of harder layers in the Drakes Bay Formation, which in this area is folded into an anticline and syncline striking northwest-southeast. The valleys are the remains of tributaries to the main stream which occupied Drakes Estero before it was flooded by the sea. At that time, the sea coast must have extended many miles further south, and the river system would have been correspondingly well developed.

Landslides

Evidence of landslides is common in the Coast Ranges. Most of the sea cliff erosion along the coast proceeds by way of local landsliding. In addition an unusually large group of ancient landslides is present along the coastline of Point Reyes Peninsula between Millers Point near the mouth of Bear Valley and Palomarin Ranch. These landslides have been described in detail by Clague (1969). The landslides are the site of the Seven Lakes, after which the Lake Ranch was named. In this dry country underlain by fractured shale, lakes are very unusual. The slide area was noticed by Gilbert (1908) but otherwise has passed formally unrecorded until recently. The northern portion of the landslide area is shown in photo 29.

Photo 29. Area of landslides at Double Point. *Photo by J. J. Clague.*

The rocks involved in the landsliding are shale, chert, and sandstone of Miocene and Pliocene age, including the Monterey Shale and Drakes Bay Formation. The landslide area unequivocally extends nearly 5 miles along the coast and about 2 miles inland. Older sliding probably extends an additional mile northward and possibly an additional mile inland.

The slides are recognized by morphological features, such as pressure ridges, steep escarpments, closed depressions, and hummocky ground, and by stratigraphic and structural features including rotated and offset bedding, disrupted strata, clastic injections, and planes of sliding.

The Wildcat, Double Point, and Palomarin slides, termed younger landslides, occurred after the cutting of the Bolinas marine terrace. The older landslides may be older than this terrace and are found inland from the younger landslides. Clague (1969) lists as causal factors:

(1) Local southwest dips in the same direction as the slope of the land.

(2) Removal of the toe of the slides by coastal erosion.

(3) The moderately steep slope of Inverness Ridge.

(4) The high permeability of the jointed shales and cherts and the seasonal precipitation.

(5) The low shearing stress of the rocks involved.

(6) Proximity to the San Andreas fault.

He concluded that the landslides attained their present form by repeated small, earthquake-triggered displacements. The major part of the younger landsliding probably took place within the last 10,000 years.

Another prominent area of landsliding involving the Drakes Bay Formation lies at the southwest end of Drakes Bay beach, exactly on latitude 38° N. The landslide area is semicircular in form with a diameter of about 2000 feet. The landslide occurred where the highest cliff of these soft beds must once have stood. The landslide is being steadily eroded away at sea level by wave action. Its fresh appearance suggests that sliding is still taking place here.

Landsliding also occurs above the sea cliff at Bolinas Point. Here the seaward 45-degree dip of the Monterey Shales and mudstones and the rapid erosion of the sea cliff contribute to the landsliding.

GEOPHYSICAL SURVEYS

The gravity field in the Point Reyes Peninsula has been described by Jones (1963), Clement (1965), Chapman (1966), and Chapman and Bishop (1968).

Clement's Bouguer gravity map on a scale of 1:125,000 covers the entire Point Reyes Peninsula. The San Andreas fault zone has no characteristic gravity anomaly associated with it, apart from effects due to contrasting densities of the surface rocks on either side.

Chapman and Bishop's Bouguer gravity map, scale 1:250,000, is superimposed on the San Francisco sheet of the Geologic Map of California. The area covered is limited on the north by latitude 38° N. which passes through Point Reyes. The scale permits the inclusion of much data obtained in the Pacific Ocean. The authors point out that "a steep gravity gradient south of Point Reyes may represent an east-trending fault that bounds the granitic rocks of Point Reyes on the south". This conclusion is supported by the geomorphology of the area.

A broad negative anomaly with an amplitude of about 50 milligals extends to the southeast from Point Reyes into the La Honda Basin. It could be caused by a prism of sedimentary rocks about 2.5 miles thick with an assumed density contrast of 0.3 grams per cubic centimeter (g/cm^3), according to Ginscom (1966).

The available magnetic data for northern California adds little to the information obtained from the gravity data.

According to Griscom (1966), "the frequent occurrence of magnetic highs over the San Andreas fault suggests that serpentinite may be more common in the fault at shallow depth than is indicated by geologic mapping". The frequent occurrence of serpentine and related rocks in the San Andreas fault zone of the Point Reyes Peninsula was noted during the present study, but no magnetic data have been published covering this area.

The U.S. Geological Survey published a map (GP—483) entitled "Natural gamma aeroradioactivity map of parts of the San Francisco region, California," by Kenneth G. Brooks

(1965). This natural aeroradioactivity is distinguished from cosmic radiation and radiation from radionuclides in the air. It comes from the upper few inches of the ground and is highest over igneous rocks or soils derived from igneous rocks and lowest over marsh areas due to the masking effect of water.

The radioactivity measured in the Point Reyes Peninsula was moderately low, varying from 400 to 500 counts per second (cps) in the southern part of the San Andreas fault zone near Bolinas to 500 to 700 cps over the granitic rocks of Tomales Point. Only the fault zone and Tomales Point were covered in the survey. These figures can be compared with readings of 800 to 1000 cps over Mount Diablo, and 300 to 500 cps over the San Francisco Peninsula.

Conclusions derived from the geophysical work briefly are as follows:

(1) The San Andreas fault zone has no characteristic gravity anomaly associated with it.

(2) An east-west trending fault in the ocean south of Point Reyes is indicated.

(3) The continuation of the Point Reyes sedimentary basin into the La Honda basin is confirmed.

(4) The occurrence of serpentinite may be more common in the San Andreas fault zone than has been recognized from geologic mapping.

GEOLOGICAL HISTORY

At this point, it is well to review the geological history of the area. This has the advantage of tying together the information presented in the preceding pages and also of giving a word-picture of conditions during the deposition of these rocks.

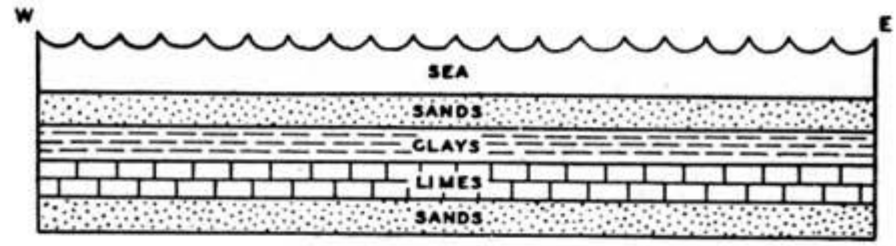
In the central part of the conterminous United States, much of which has been relatively stable for long stretches of geological time, geological history normally consists of alternating invasions of the continent by the sea and deposition of marine sediments, followed by relative uplift of the land and consequent erosion. In central California, however, the situation is more complicated, since it seems likely that, at least since Cretaceous times, horizontal movement has been taking place along the San Andreas fault. Assuming that right-lateral displacement on the San Andreas fault has been continuous at a lower-than-average rate of around one-half inch per year, then the following displacements along the fault could have taken place:

1 mile in 125,000 years.
4 miles in 500,000 years.
8 miles in 1,000,000 years.
80 miles in 10,000,000 years.

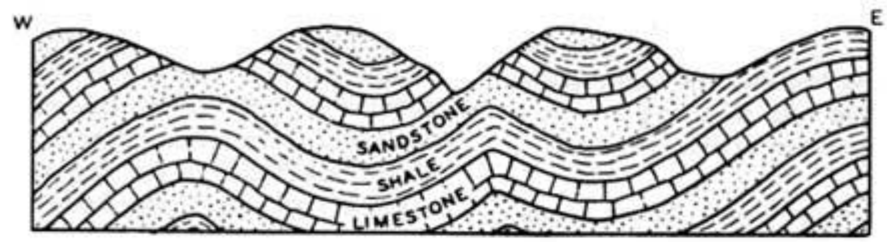
Thus, at the beginning of the Pliocene (about 10 million years ago), the rocks of the Point Reyes Peninsula might have been about 80 miles south of their present position, relative to the mainland. Changes in relative elevation of land and sea can be readily discerned in the rocks, but it must be remembered that lateral movement was also taking place at the same time.

PreCretaceous through Pleistocene

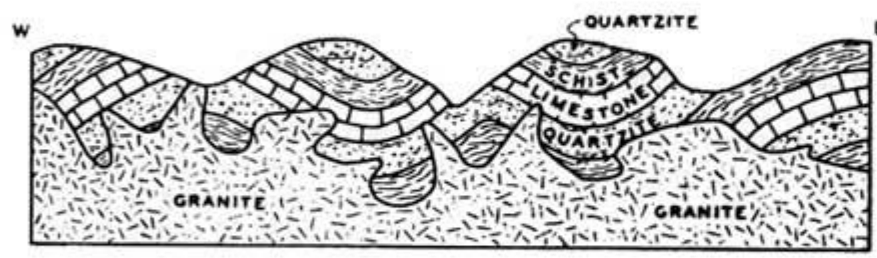
The oldest rocks of the Point Reyes Peninsula are the metamorphosed crystalline limestone and schist which appear as roof pendants (remnants) in the granitic rock. These rocks are older than the granitic rock which engulfed them and were originally deposited as layers of sand, clay, and soft lime in a shallow sea (figure 5a).



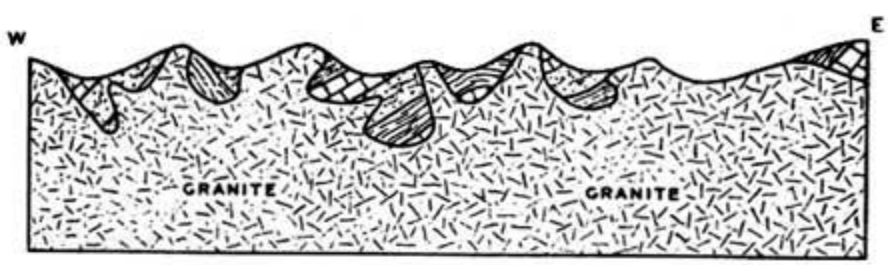
A. Layers of sand, clay, and lime were deposited in a shallow sea.



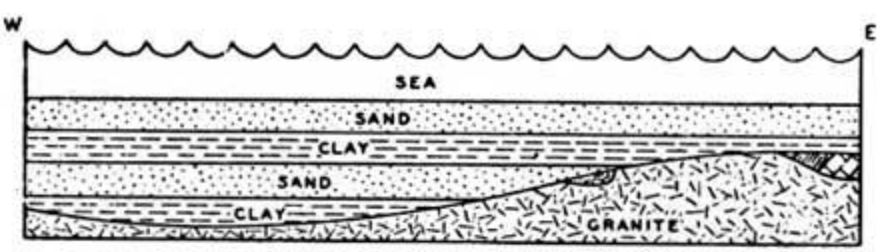
B. Sedimentary layers were compacted into soft rocks, then folded, and eroded when land mass was elevated above the sea.



C. Pressure and heat of molten granite which intruded the soft rocks changed them into hard metamorphic rock.



D. Partial erosion of metamorphosed rock exposed granite leaving pendants of former roof rock.



E. Granite was covered by layers of new sediments when ocean covered the land.

Figure 5. Diagrammatic sequential cross sections illustrating general geologic history of Point Reyes Peninsula.

Millions of years later the sediments had become compacted and perhaps had been uplifted and folded by great earth movements (figure 5b). They were invaded by a mass of molten rock rising from the depths of the earth, which solidified into granite (figure 5c). The heat and pressure caused by this granite intrusion changed, or "metamorphosed", the old sedimentary rocks into the hard quartzites and crystalline schists and limestones now seen as remnants or roof pendants. Their age is unknown, but they are older than the granitic rock which engulfed them. The age of the granitic rock has been determined by Curtis and others (1958) to be about 84 million years (middle Upper Cretaceous).

The granite is exposed continuously between Tomales Point and Mt. Wittenburg near Olema, and it forms the prominent cliffs at Point Reyes. At the time the molten granitic material was emplaced, it could have been hundreds of miles south of its position today. This possibility is not hard to envisage since granitic rock similar to that of Point Reyes is present on the mainland or east side of the fault in the Tehachapi Mountains at the south end of the San Joaquin Valley; the Point Reyes granitic rock could once have been part of that mass.

Following the emplacement of the molten granitic material 84 million years ago, millions of years probably elapsed while it cooled and solidified.

The solidified granite and its covering of metamorphosed sediments were lifted up to form mountains, which were then eroded by wind and rain (figure 5d). Probably most of the metamorphosed sediments and part of the granite had been eroded away when the sea started to encroach again (figure 5e). The oldest sediments found lying on top of the granite are Paleocene in age, or about 60 to 70 million years old. At Double Point Paleocene rocks cored in a deep well are quite fine-grained and marine, suggesting fairly deep sea at this locality; but at Point Reyes itself the Paleocene is a coarse conglomerate, suggesting shallow water and proximity of land. The conglomerate contains pebbles and cobbles of lava and other rock not found now in the vicinity. Their hardness and roundness suggest they may have been derived from an earlier conglomerate of which there is no other evidence today. Perhaps in late Cretaceous time, the granitic basement was uplifted above the sea in the vicinity of Point Reyes, and a conglomerate was formed which was afterwards reworked by the sea when faulting was renewed in Paleocene time. This supposition does not seem unreasonable, since Cretaceous rocks are present west of the San Andreas fault at Gualala to the north and at Montara Mountain to the south, although not exposed in the Point Reyes Peninsula. Similar lava cobbles are found in Paleocene conglomerate at Carmel Bay.

Thus, in the vicinity of Point Reyes, the land must have risen to some extent above the sea in Paleocene time 60 to 70 million years ago (figure 5f). No trace of Cretaceous or Paleocene rocks on the granitic basement along Inverness Ridge has been found, suggesting they were never deposited there.

The next episode of which we have evidence is the sinking under the sea of the Point Reyes Peninsula, including Inverness Ridge and Tomales Point, in early Miocene time 20 to 25 million years ago, with the resultant widespread deposition of the Miocene Laird Sandstone, derived from the granitic rock of the area. The land was covered gently by the sea, and the Laird Sandstone accumulated in shallow water as the sea advanced. In the lower spots, considerable thicknesses of Laird Sandstone accumulated.

As Miocene time continued, the supply of sandy material diminished as the granitic mass was covered by the sea. The conditions offshore then became similar to those at many other localities in central California that were favorable to the deposition of Monterey Shale. These conditions as listed by Bramlette (1946) include: (a) fairly deep marine basins off shore, (b) a minimum of clastic material being brought into the basin, and (c) high availability of silica, possibly due to vulcanism, resulting indirectly in the widespread development of diatomaceous rocks.

Somewhat similar conditions prevail today in the marine basins off the coast of southern California (Emery, 1960).

During Miocene time 10 to 25 million years ago, the Point Reyes Peninsula rocks were situated 100 miles or more southeast of their present position. Post-Miocene lateral movement on the San Andreas fault amounted to 125 miles, which would mean that the Point Reyes Miocene was laid down when the underlying rocks were situated about where the Pinnacles National Monument is today (Berry and others, 1966).

No individual ash beds or lavas are seen in the Miocene of Point Reyes Peninsula. Nevertheless, the Miocene Monterey Shale of Point Reyes contains very fine-grained, ash-like material, which indicates that volcanic activity was close enough for the ash to be carried into the area by wind. Conditions were favorable for the formation of the siliceous Monterey Shale in the offshore basins which must have existed at that time.

The area continued to submerge during the Miocene epoch. The late Miocene marine sediments are much more widespread than the middle Miocene, indicating the continuation of the relative sinking of the land areas during late Miocene time. At the end of Miocene time, most of the peninsula mass was under the sea. Perhaps it resembled the Channel Islands as seen from Santa Barbara.

The next page in the geological story is represented by the Pliocene Drakes Bay Formation, which forms the white cliffs of Drakes Bay. The sandstone at the base of this formation has been determined to be a little less than 10 million years old. It must, therefore, have been laid down very soon after the end of Miocene time; however, a retreat and reinvasion of the area by the sea are indicated by the widespread, coarse, glauconitic sand developed at its base.

This basal greensand contains many bones of sharks and marine mammals, indicating that the water in which it was laid down was quite shallow. In the northern part of the area, there is a strong unconformity between the Pliocene Drakes Bay Formation and the underlying Miocene (photo 30), showing that in that part of the Peninsula at least, the Miocene beds were uplifted between Miocene and Pliocene time and eroded, after which the Drakes Bay beds were laid down on top of them unconformably. The existence of this unconformity to the north suggests that deeper water lay to the south, in the direction of the La Honda Basin.

Photo 30. Miocene-Pliocene unconformity near the U-Ranch. The Pliocene Drakes Bay Formation overlies contorted Miocene Monterey Shale on the east side of the Point Reyes syncline.

The predominance of very fine-grained material in the Drakes Bay Formation suggests that little granitic rock remained above water at this time. Much of the siltstones and mudstones of this formation may well have been formed by the reworking of Monterey Shale, which they resemble closely except for the lack of rhythmic bedding. Many of the diatoms in the Drakes Bay Formation are Miocene varieties which may also have been reworked, although they may well have survived into early Pliocene times.

Probably before deposition of the Pliocene Drakes Bay Formation ceased, deposition of the younger Merced Formation commenced in the depression occupied by the fault zone near Bolinas, seems likely that the depositional basin of the Merced Formation at Bolinas was connected by a seaway to the depositional basin of the type area south of San Francisco and east of the fault zone. The sea was shallow as indicated by abundant fossils in the formation. However, the type section at Seven Mile Beach is 5000 feet thick compared with a few hundred feet at Bolinas. Perhaps the Bolinas depositional basin was a shallow inlet comparable to Tomales Bay today, connected with the main depositional area of the Merced which lay to the southeast. This main depositional area to the southeast was also a sheltered basin (Glen, 1959) and apparently was separated by land (Inverness Ridge, probably) from the Bolinas basin of deposition.

The Merced Formation of the Point Reyes Peninsula did not extend up the fault zone beyond the topographic high at Five Brooks, unless subsequent erosion has removed it. (The so-called "Merced" formation of the Dillon's Beach area is different in lithologic facies from the type area and from the Bolinas area; it seems not to have been connected to the Bolinas area, but to have been laid down in a sea which extended east toward Petaluma.)

At the end of the deposition of the Merced Formation, the sea was becoming very shallow in the Bolinas area. The topmost beds of the Merced Formation are sands and gravels such as might have accumulated in a backbeach area. The age of these beds is possibly Pleistocene like the top section of the Merced Formation in the type area.

At about this time, or possibly a little later, beds of a very different kind were being laid down at the Tomales Bay end of the fault zone depression. The high area around Five Brooks exhibits rocks of the Franciscan Formation at the surface, indicating that, if any beds of Pliocene-Pleistocene age were laid down in that vicinity, they were subsequently eroded. But northwest of Five Brooks, a large Pleistocene fresh-water lake developed in the fault zone depression, extending as far north as Point Reyes Station or perhaps Millerton. Beds laid down in this lake include silty mudstones containing fresh-water diatoms and gravelly beds of white "granite wash" derived from the west. These fresh-water lake beds form the Olema Creek Formation. (Today no granitic rocks are present close to Five Brooks; but, assuming right-lateral movement has been continuous on the San Andreas fault, they could well have been immediately west of the fault zone when the granitic debris was deposited in the Olema Creek Formation.) The exact age of this formation is unknown, but the following facts are helpful in dating it.

(1) It contains fresh-water diatoms which are all Holocene forms.

(2) It contains remains of tree trunks with a C—14 age of about 38,000 years.

(3) It is quite young in appearance and degree of consolidation.

(4) It dips at angles as steep as 45 degrees.

(5) It has apparently moved southeasterly down the fault zone at least some 12,500 feet which, assuming a rate of movement of 2 inches per year, would suggest an age of 75,000 years.

It is not known how far north these fresh-water beds extended; however, mudstone of a similar appearance underlies the terrace deposits at Point Reyes Station, and at Millerton the lowest beds are reported to be fresh-water deposits (Mason, 1934). The marine fossiliferous beds overlying them are reported to be more than 50,000 years old (Richards and Thurber, 1966).

Thus, the Olema Creek Formation is probably partly contemporaneous with the Millerton Formation (late Pleistocene).

The Bolinas—Drakes Bay terrace extending discontinuously from Bolinas to Drakes Bay consists of a prominent wave-cut platform overlain by landlaid terrace deposits (photo 21). The terrace deposits consist almost entirely of Monterey Shale debris washed off the nearby steep hills. At its base is a thin bed resembling a soil and a layer of rounded pebbles.

To account for the formation of this terrace, we must first postulate a high stand of the sea in post-Merced time, with wave erosion forming the wave-cut platform on which the town of Bolinas stands and on which the terrace deposits were laid down further north. Then the sea retreated, possibly to a level considerably lower than present sea level, thus uncovering the flat platform which had been cut by the waves in the underlying rocks. The wave-cut platform was then tilted northward by tectonic forces; terrestrial deposits accumulated on its tilted surface and formed a new level surface with a thicker section at Drakes Bay than near Bolinas. Then the sea gradually rose to its present level, and nearly all of the once extensive terrace was eroded away. The retreat of the sea cliff in these soft beds could be on the order of at least a foot a year, so that in 50,000 years the cliff has been eroded back many miles.

Subsequent earth movement has lowered the terrace deposits below present sea level at Drakes Bay. It seems possible too that there has been some tectonic uplift at Bolinas and at Tomales Point, though this movement is difficult to separate from the eustatic changes in sea level.

As mentioned earlier, it seems very likely that the age of the Bolinas—Drakes Bay terrace is about 100,000 years. Studies of the great Ice Age of the Pleistocene show that there was a marked melting of the ice caps in the Sangamon interglacial stage about 100,000 years ago. The water derived from this melting ice raised sea level everywhere and no doubt caused the marine incursion which formed the Bolinas-Drakes Bay wave-cut platform. Subsequently the sea retreated again as more water was frozen in the increasing ice caps of the Wisconsin glaciation. The melting of the ice caps since that time (about 20,000 years ago) has resulted in a rise in sea level from about 125 meters to the present sea level. This is the marine transgression referred to as Flandrian by Cooper (1967) in his work on the coastal sand dunes.

Numerous obscure terraces are present along the coast at elevations higher than the Bolinas-Drakes Bay terrace, but they are too discontinuous to draw any conclusions about the geological history they represent. The same applies to the mature rounded land forms to be seen at higher elevations along Inverness Ridge. One group of deposits however, deserves mentioning here because they do give information about the past. These are the terraces with cobbles of Franciscan chert mentioned on page 44. It seems necessary to assume that these Franciscan Formation remains came from east of the fault zone and in a downhill direction so that they must have crossed the fault zone before it was eroded by streams. If so, they must have been deposited long ago, perhaps in late Pliocene times or early Pleistocene.

ECONOMIC GEOLOGY

Coal and Peat

In the last half of the 19th century, before abundant oil was discovered, strenuous efforts were being made in California to locate supplies of coal as a substitute for wood for fuel. Two explorations for coal on Point Reyes Peninsula were reported. The first one was on the Nelson Olds (now Boyd Stewart) Ranch near Olema, where a prospecting tunnel 325 feet long was dug in 1875 *(Marin Journal,* November 8, 1875). The location is in the lakebeds of the Olema Creek Formation (Pleistocene?), which are very peaty. Evidently not enough peat was found to justify further work. These peaty beds can be seen in the roadcut on the east side of State Highway 1, just south of the entrance to the Boyd Stewart Ranch.

Parker (1893) mentions specimens of "coal" from the banks of Pine Gulch Creek near Bolinas. Watts (1893) mentions that "some prospecting for coal has been done about 2 miles north of Bolinas, on the McGovern Ranch. No coal, however, is in sight, the formation exposed being a dark colored shale." This prospect hole, excavated in dark grey-black Monterey Shale on the bank of Pine Creek Gulch, is still referred to as "the coal mine" by nearby ranchers.

Gold

The *Petaluma Journal and Argus* of February 15, 1868, has the following lively description of a gold discovery on Tomales Point:

"There was quite an excitement created by the discovery of gold on the beach at Pierce's Point, which forms the southern share at the entrance of Tomales Bay. Some men from Preston's Point crossed over to the place above named to gather mussels, and one of them while drinking from a brook that came down from the bluff, discovered some scale gold. Procuring a pan they got good prospects, which induced them to construct a sluice, through which they washed the earth from the bottom of the ravine, realizing $15.00 to the hand for a day's work. Where they worked is only accessible at low tide. We would not counsel a rush of over ten thousand miners to the new diggings."

Munro-Fraser (1880, p. 311) says,

"At Tomales Point there is a place called Gold gulch, where sluices were put in and placer mining carried on quite extensively in 1865-66, and the yield averaged two dollars and a half a day to the man. It is fine flake dust, hence much of it was lost. Lack of water caused them to abandon the enterprise. There are also quartz lodes here that promise well. Seven assays averaged of gold thirty dollars and eighty-three cents and of silver fifty four dollars and ten cents."

Trask (1856, p. 13) writes that "at Point Tomales on the west shore of the bay, gold also abounds but in small quantity. It is found about one mile from the northern end of the point, near the settlements on that shore." Irelan (1888, p. 342) reports "on the ocean side of Tomales Point occurs a deposit of auriferous black sand. It can only be reached at low tide." Ver Planck (1955) mentions a prospect shaft, probably sunk for gold, near Willow Point on Tomales Bay. These occurrences apparently were not sufficiently large to encourage further exploration and nothing more is known of them today. However, panning the streams and beaches near these localities might yield interesting results. (Landowners' permission would, of course, be required.)

Greensand

Greensands, or sands containing glauconite, a green mineral which is essentially a hydrous potassium iron silicate, have occasionally been used commercially as water softeners and as a source of potash for fertilizer. Considerable concentrations of glauconite occur in the greensand at the base of the Drakes Bay Formation; however to the writer's knowledge the material has never been exploited here and it is not known whether the occurrence is commercial.

Limestone

Limestone for the manufacture of cement was naturally in great demand in the early days of San Francisco; and before supplies became available from the large quarries south of the city, efforts were made to develop some of the local deposits in the Point Reyes Peninsula. Small kilns and quarries are found 3/4 mile west of Inverness Park; these are referred to by Blake (1856), who writes "thick beds of good white limestone" are found near Tomales Bay "which are quarried and calcined for the San Francisco market." This Inverness Park exposure is referred to in the literature also as "the Lockhart tract" or the "Trout Farm" quarry. Anderson (1899) refers to it as being "on the 'old road' which crosses the summit from the head of Tomales Bay."

The accompanying geologic map shows that the Inverness Park (Lockhart) limestone is associated with nearby limestone exposures to the south in Haggerty Gulch and on the Noren property. The intervening area is covered with vegetation, so it is possible that the limestone of Inverness Park is more extensive to the southeast than shown. The main outcrop on the old Laguna Ranch road is covered on the southwest side by Miocene sediments, so it could extend in this direction also, as suggested by Eckel (1933). However, there is considerable faulting in this area, as is indicated by the anomalous shape of the nearby contacts, and core drilling would be necessary to explore under the Miocene cover before any assumptions as to its extension westward could be safely made.

Two core holes have been drilled in the area by a cement company. One encountered only granitic rock which was deeply weathered to about 60 feet, and the other encountered limestone which was probably interbedded with schist and impregnated with granitic material. It was concluded that the deposit was not of sufficient size nor thickness to be of economic value. Examination of the Haggerty Gulch outcrops bears out this conclusion since the limestone there occurs in thin beds interbedded with schist and permeated with stringers of igneous rock.

This, too, is characteristic of the other metamorphic limestone occurrences shown on the map; namely, those on Mt. Wittenburg, and on the Bender place at Willow Point. As additional subdivision roads are cut in the Inverness area, more limestone occurrences may be exposed, but the possibility does not seem to be good that any of them will be of economic value because: (1) known occurrences are all thin-bedded and intermixed with schist and granitic material and (2) the surface mapping has been sufficiently detailed to have detected any extensive body of thick limestone, except in the densely vegetated areas.

In addition to the limestones of the metamorphic group, two occurrences of Calera (Franciscan) limestone in the San Andreas fault zone have been observed. One of these is at the well known so-called Russian lime kilns near Five Brooks, described in interesting detail by Treganza (1951) and already described in this report. The outcrop at the Russian lime kilns is quite small, and it appears to be a tectonic inclusion in the fault zone. There is little reason to think it extends laterally much beyond the outcrop area, although some fragments of limestone are to be found in the fault zone about 1000 feet to the southeast.

The other occurrence is located about 2 miles southeast of the Russian lime kilns and is marked by the presence of old kilns. Presumably the outcrop is similarly limited in size, although the outcrop is too badly obscured to be able to determine its size. Limestone analyses made by previous workers are listed in table 11. While there are numerous limestone outcrops in the area, and more will probably be found, it seems unlikely that an economic deposit exists, because of the interbedding of the pure limestone layers with beds of schist and permeation of the whole with intrusive igneous rock.

Table 11. Analyses of limestones. *Adapted from Eckel, 1933, p. 358.*

Location no.	*SiO_2 (%)*	*Al_2O_3 (%)*	*Fe_2O_3 (%)*	*$CaCO_3$ (%)*	*CaO (%)*	*$MgCO_3$ (%)*	*MgO (%)*	*CO_2 (%)*
1	1.66	0.44	0.20	96.60	n.d.	0.75n.d.	n.d.	
2	2.26	0.55	0.25	95.48	n.d.	1.10	n.d.	n.d.
3	2.3	0.76	incl.	96.0	53.8	n.d.	0.35	42.7
4	1.3	0.3	incl.	97.0	54.32	n.d.	1.25	42.68

5	n.d.	n.d.	0.35	97.50	n.d.	1.60	n.d.	n.d.
6	1.1	0.68	incl.	97.8	54.8	n.d.	tr.	43.2
7	1.90	0.76	0.20	96.74	n.d.	0.33	n.d.	n.d.

Location no.:

[1]Old quarry near Trout Farm. Marin County. Sampled and analyzed by C.A. Newhall.

[2]Lockhart tract near Inverness Park. Marin County. Sampled and analyzed by C.A. Newhall.

[3]Lockhart tract near Inverness Park. Marin County. Sampled by E.C. Eckel, analyzed by U.S. Bureau of Standards.

[4]Near Inverness Park. Marin County. Sampled and analyzed by F. Huber.

[5]West of head of Tomales Bay. Analysis given by Anderson (1899).

[6]Russian lime kiln. south of Olema, Marin County. Sampled by Junes Kelly. analyzed by U.S. Bureau of Standards.

[7]Russian lime kiln, south of Olema, Marin County. Sampled and analyzed by C.A. Newhall.

Petroleum

Abundant signs of petroleum are present on the Point Reyes Peninsula, but no commercial production has been established. Along the beaches and cliffs between Duxbury Point and Double Point, oil-filled joints are conspicuous in the Monterey Shale, and thick tar and oil-sands occur at the Miocene-Pliocene contact from south of Double Point northward to Bear Valley. The sandstone dikes which are common in this vicinity are often bituminous. A spectacular gas seep in the Duxbury Point area was reported by Holder (1893), the *Marin Journal* (January 5, 1893), Crawford (1896), St. Amant (1905), Bingham (1906), Douglas and Rhoades (1915), and Bradley (1915). This seep, which apparently was big enough to cook fish on when lighted, is not evident today. Judging by the descriptions, it probably emerged from a joint-plane fissure in the Monterey Shale. Erosion of the cliff has doubtless resulted in the seep now being covered by the sea and beach. Further north, near Double Point, the writer has observed an active oil and gas seep visible at low tide.

Attracted by the oil and gas seepages along the coast near Duxbury Point and Arroyo Hondo, and encouraged by the discovery of oil in Humboldt County, the Arroyo Hondo Petroleum Company, backed by George T. Hearst and others, drilled a shallow wildcat well at the mouth of the Arroyo Hondo in 1865. At the same time another well was drilled by the Bolinas Petroleum Company, on the point at the entrance of Bolinas Bay. Enthusiasm ran high, and the Petroleum Hotel was established at Bolinas, but no oil in commercial quantity was found. The wells were very shallow, not over 400 feet in depth, and no information is available on their findings. Apparently the Arroyo Hondo well was drilled entirely in Monterey Shale, and the Bolinas well in Merced Formation.

From 1900 to 1906, there was more oil exploration with two or three wells drilled in the vicinity of Duxbury Point, on the Garzoli Ranch. The casing of one well can still be seen sticking out of the cliff at the intersection of Rosewood Road and Ocean Parkway on Bolinas Mesa. These unsuccessful wells were about 2000 feet in depth and one was drilled to 2800 feet and reportedly produced a few barrels of heavy oil per day from the Monterey Shale. The report of this small production does not seem improbable in view of the oil filled joints and the historic gas seep at this location. Another shallow dry hole was drilled at this time near Arroyo Hondo.

In the 1950's another group of wells was drilled. Several of these were relatively deep and were located with the aid of careful geological work, but again none was successful. Table 12 presents data on these exploratory wells.

Table 12. Records of exploratory wells to April 1, 1970.

M. D B & M.[1] *T*	*R*	*Sec*	*Name of company and well*	*Date started*	*Date abandoned*	*Total depth (feet)*	*Geology*
3 N	9 W	36	P.M. Oil Company, No. 1		1954	1671	0-917 ft. Alluvium. 917-1671 ft. Franciscan.
2 N	10 W	4	Standard Oil Co., Molseed No. 1	1951	1951	1780	0-1620 ft. Drakes Bay Formation, Pliocene. 1620-1780 ft. "Granite". (Corehole)
2 N	10 W	17	Standard Oil Co., Mendoza No. 1	5-51	1951	951	0-854 ft. Drakes Bay Formation, Pliocene. 854-951 ft. "Granite".
2 N	10 W	17	Standard Oil Co., Mendoza No. 2	1951	1951	1276	0-1248 ft. Drakes Bay Formation, Pliocene. 1248-1276 ft. "Granite". (Corehole)
2 N	8 W	33	Standard Oil Co., Robson No. 1	5-52	1952	7286	0-7286 ft. Entire section in Monterey Shale.
1 N	8 W	7	Standard Oil Co., (L.M. Lockhart,) Tevis No. 1	9-47	1951	6587	Drilled to 5123 ft. by L.M. Lockhart and abandoned Jan. 1948. Standard Oil Co. took over the well April 1951 and deepened it to 6587 feet. 0-4685 ft. Monterey Shale including Mohnian, Luisian and Relizian. 4685-4795 ft. Laird sand. 4795-4910 ft. shale. 4910-5015 ft. volcanics. 5015-6587 ft. Lower Eocene, "C" zone or Paleocene.
1 N	8 W	21	Arroyo Honda Pet. Co.	4-1865	1866	375	Unknown.
1 N	8 W	17	W.A. Sherman, South End Ranch	1903?	1905?	?	Unknown.
1 N	8 W	35	Leroy G. Harvey, Garzoli No. 1[2]	1901	1905?	1800	Dry hole in Monterey. Showings at 700 ft. and 1200 ft.

1 N	8 W	35	Leroy G. Harvey, Garzoli No. 2		1905?	2200	Dry hole in Monterey. No showings.
1 N	8 W	35	Leroy G. Harvey, Garzoli No. 32		1905?	2700-2800	Abandoned in Monterey. Reported a few barrels per day of low gravity oil. Casing still shows in cliff.
1 N	8 W	26	Lockhart, L.M., R.C.A. 3-1	9-48	1949	8409	Base "Santa Margarita" 2840 ft. Upper Mohnian 2840-4880 ft. Lower Mohnian 4880-8310 ft. Luisian 8310-8409 ft. Laird sandstone not reached.
1 N	8 W	25	Bolinas Pet. Co. Nott No. 1	1865	1865?	80	Unknown.
1 N	8 W	?	Houston Jones	1891	?	?	Unknown.

[1]Projected township, range, and section is from "Regional *Wildcat Map" W6-1 of the California Division of Oil and Gas, January 15, 1966.*

[2]The casing of an abandoned oil well, presumably one of the Garzoli wells since it is on the old Garzoli ranch, is to be seen about 100 feet northeast of the Clubhouse on Bolinas Mesa. The casing of another abandoned well, believed to be Garzoli No. 3, can be seen in the cliff face at the intersection of Bosewood and Ocean, on Bolinas Mesa.

Although indications of petroleum are abundant, the presence of a good reservoir bed is questionable. The thick oil sands near Double Point are probably of local occurrence.

The Monterey Formation is mostly shale and no favorable beds are present except for the basal Laird Sandstone. This sandstone seems to be both porous and permeable in the outcrop, where it overlies the granitic basement; but in the Standard (Lockhart) Tevis #1 well at North Double Point, the probable correlative sand at a depth of 4690 to 4790 feet consisted of gray water-saturated sand in the lower part and seemed to be hard and impervious in the upper part. This sand is probably present as a possible objective in the area; but whether it is present everywhere in this area and whether it is sufficiently permeable is not known in the absence of further drilling.

Most of the anticlines noted in the section on local folds seem to be too small for an accumulation of oil which would justify the risk of drilling, even if other conditions were favorable.

Fault traps usually combine vertical faulting with a structural feature such as an anticline. Numerous faults are mapped or suspected in the area, but many of these are probably lateral in direction of displacement rather than vertical. Uncertainties in the mapping of anticlines apply equally to the mapping of any subsurface structural features associated with anticlines.

Stratigraphic traps are formed when oil or gas accumulates in the up-dip edge of a discontinuous sand or locally porous bed. The 100-foot sand which occurs in the Standard (Lockhart) Tevis #1 well at 4690 to 4790 feet probably diminishes in thickness northward approaching the basement and must terminate eastward against the San Andreas fault zone. Westward its position is unknown, but possibly it is present under the siltstones of the Drakes Bay Formation in the Point Reyes syncline.

In any of these situations, the geometry of the sand at some point might be such that oil or gas could accumulate; but it would be necessary to drill a series of exploratory tests to find such a trap, and the expense involved would appear to be far greater than the chances of success justify.

The structural complexity of the area, caused by the proximity of the San Andreas fault, and the small size of the structures that can be mapped, make the possibilities for commercial oil or gas accumulations unlikely, in spite of the numerous local oil and gas showings and the possible presence of a reservoir sand at depth.

Scheelite

Scheelite, a tungsten mineral (calcium tungstate, $CaWO_4$) associated with limestone roof-pendants in the granitic rock, has been found at the Noren and Bender localities on the west side of Inverness Ridge. Neither has any commercial importance under present [1974] economic conditions.

Stone

A granite quarry was opened in 1854 at the east end of Point Reyes, at the point where the fishing-boat piers are now [1974] situated. This development was not successful, probably because the rock was so broken by faulting that no large blocks could be recovered.

Weathered granitic rock has been quarried for road material near the top of Inverness Ridge on the Drake's Summit road. This rock is badly decomposed and can be handled almost like gravel. Similar gravel pits are to be found in the vicinity of Inverness.

Small pits or quarries have been opened by ranchers in the Monterey Shale for the extraction of road material. The shale makes a very dusty road in summer, but it packs and drains well in the wet weather.

Water Supply

A detailed coverage of the water supply of the Point Reyes National Seashore is given by Dale and Rantz (1966).

As previously mentioned, precipitation on the peninsula is highly seasonal and more than 75 percent of the annual amount falls in the five months November through March. Consequently, 90 percent of the annual runoff occurs in the five months December through April, and many of the minor streams are intermittent in character, drying up in the late summer. For a reliable water supply, therefore, either perennial streams or porous and permeable aquifers must be utilized.

There are numerous perennial streams on the west side of Inverness Ridge, including Arroyo Hondo from which Bolinas obtains a water supply, Alamea Creek which meets the ocean just north of Double Point, Bear Valley Creek, and Glenbrook Creek. These streams have a relatively large drainage area on the southwest slopes of Inverness Ridge.

On the east side of Inverness Ridge, Olema Creek and Pine Gulch Creek flow northwest and southeast, respectively, along the San Andreas fault zone. These two streams are perennial. The precipitation map (figure 6) shows that rainfall on Inverness Ridge is the main source of water for these streams.

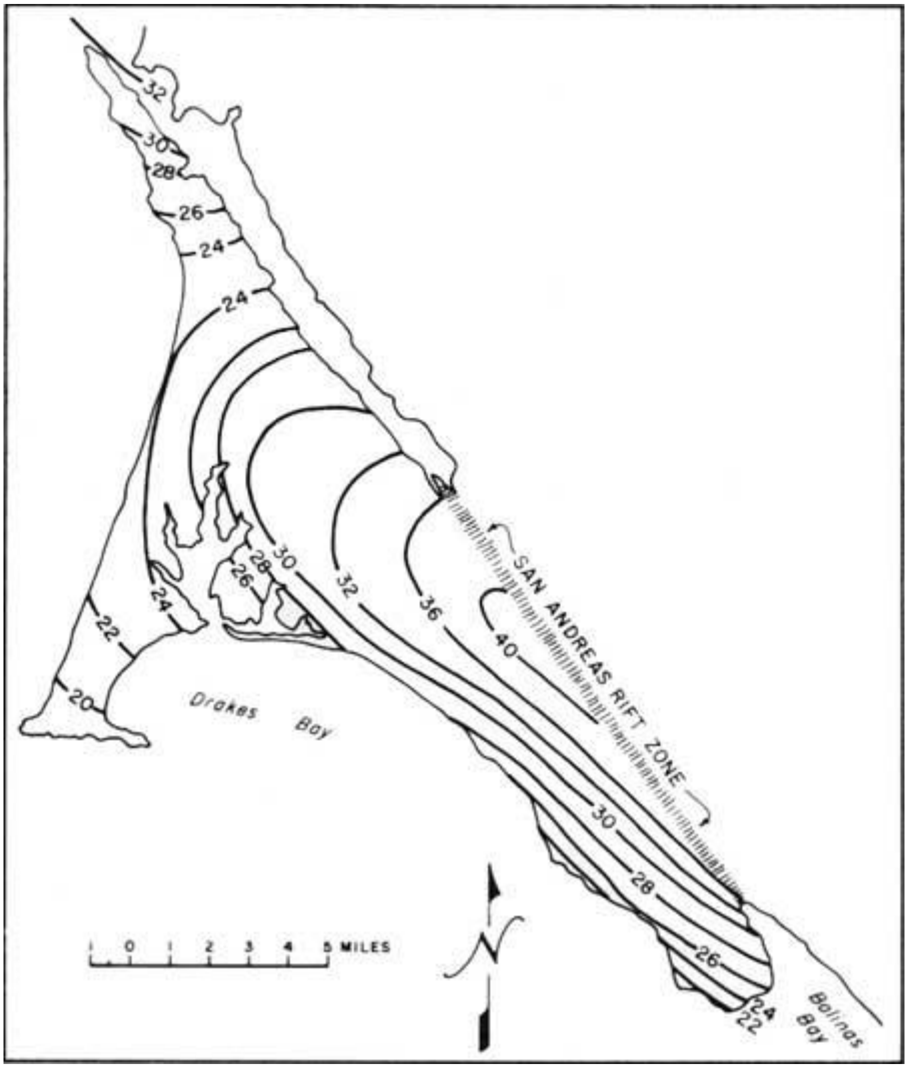


Figure 6. Precipitation map, Point Reyes Peninsula. Contours are isohyets of average annual rainfall, in inches. *Adapted from Dale and Rantz, 1966.*

In the synclinal area occupied by the Drakes Bay Formation and at Point Reyes, there are no streams of importance. Water discharges in small amounts from the dune sands and older beach deposits along Point Reyes Beach, and at McClures Beach a perennial creek draws its supply from these sources. Table 13 presents the flow of some of some streams on Point Reyes Peninsula.

Table 13. Low flow characteristics of streams on Point Reyes Peninsula (after Dale and Rantz, 1966).

Name of stream and measurement point	Discharge exceeded 60% of the time (gpm)	Discharge exceeded 90% of the time (gpm)	Firm yield.[1] (gpm)
Pine Gulch Creek (near Woodville)	410	190	60
Alamea Creek (near Crystal Lake)	420	270	180
Bear Valley Creek (1 mile south of National Seashore Hq.)	153	75	30
Glenbrook Creek (close to Monterey—Drakes Bay contact)	103	18	0
McClure Creek (close to beach)	66	40	25

[1]Firm yield is a discharge of such magnitude that only on one Labor Day in 25 years, on the average, will it fail to be obtained.

The quality of the water on the peninsula is reported to be good for domestic use. Few of the geologic formations present in the Point Reyes Peninsula form good aquifers. The granitic basement is generally a poor aquifer, with wells yielding generally less than 1 gallon per minute. No water wells are reported in Paleocene sediments, and the Paleocene conglomerate exposed at Point Reyes appears to have little porosity or permeability.

The Laird Sandstone, if saturated, might be expected to yield about 10 gallons per minute to wells. The Monterey Shale and Drakes Bay Formation are unsatisfactory for water supply. In the vicinity of Bolinas domestic water wells in the Merced Formation yield 5 to 25 gallons per minute.

The most productive aquifers are coarse sands and gravels of Quaternary age. Wells in the sands yield up to 60 gallons per minute, but the gravels grade into clay and silt of the tidal marshes where the yield drops to less than 2 gallons per minute. The dune sands and older beach sands of Point Reyes Beach appear to form good porous and permeable ground-water reservoirs.

Table 14. Point Reyes Peninsula ranches and localities.

Name used this report	*Name used by Gilbert (1908)*	*Other names*	*Latitude and Longitude*	
			N Jat	*W long*
AT&T radio station	"Post office"	E. Gallagher	38°05'31"	122°57'16"
Bear Valley Ranch	Skinner, W.D.	Howard, Kelham, Abbott, W.H., Seashore Headquarters	38°02'39"	122°47'50"
Beisler	Beisler	Part of Hagmaier Dream Farm	37°58'28"	122°44'07"
Bender			38°05'21"	122°50'40"

Clam Patch	Clam Patch		37°54'09"	122°41'19"
Glenn Ranch		Part of Kelham	37°59'25"	122°47'17"
Grossi (A.) Ranch			38°07'01"	122°55'31"
Grossi (D.) Ranch			38°06'32"	122°54'12"
Hagmaier Ranch	Bondietti		37°58'16"	122°43'47"
Heims Ranch			38°05'24"	122°54'45"
Hall Ranch			38°02'09"	122°57'42"
Hamilton	Hamilton (barn)	Willow Point	38°05'24"	122°50'33"
Home Ranch		Murphy	38°04'22"	122°54'19"
Kehoe Ranch			38°09'35"	122°56'12"
Laguna Ranch		Marshall	38°02'39"	122°51'39"
Lagunitas Creek	Papermill Creek			
Lake Ranch	"Seven Lakes"		37°56'54"	122°45'25"
Lockhart Ranch	Sunshine	Sunny Side	38°03'40"	122°50'01"
McClure, J., Ranch			38°08'06"	122°56'22"
Mendoza Ranch			38°00'56"	122°59'16"
Molseed Ranch	Claussen	Marvin Nunes	38°03'30"	122°58'14"
Muddy Hollow Ranch			38°02'58"	122°52'07"
Noren residence			38°03'36"	122°49'01"
Nunes, George, Ranch		(ex Mendoza)	38°00'01"	122°59'39"
Ottinger Ranch		Vision	38°06'28"	122°52'53"
Palomarin		Religious Colony, Church of Golden Rule	37°56'06"	122°44'51"
Pepper Island		Kent Island		
Pierce, Lower, Ranch		McClure	38°13'26"	122°58'39"
Pierce, Upper, Ranch		McClure	38°11'25"	122°57'12"
Pig Ranch		Pig Farm	37°59'51"	122°49'11"
RCA radio station		Lunny, McClure	38°05'44"	122°56'45"
Righetti Ranch	Southworth	Riverside	37°56'42"	122°42'28"
Rogers Ranch		"Old blacksmith shop"; (ex Grossi)	38°05'37"	122°54'50"
Sky Farm		Part of Kelham	38°02'24"	122°49'36"
Spaletta Ranch		T. Gallagher	38°02'27"	122°58'47"
Steele Ranch		Marquis	37°56'00"	122°41'54"
Stewart, Boyd, Ranch	Dickson Ranch	"Woodside", Olds	38°00'32"	122°45'46"

Stinson Beach	Willow Camp		
Texeira Ranch	Strain, E.R.		37°57'12" 122°42'51"
Truttman	Bloom		38°01'32" 122°46'32"
U Ranch		Part of Kelham Olema Ranch	38°01'06" 122°51'13"
Vedanta Retreat	Payne Shafter Place	"The Oaks"	38°02'09" 122°47'25"
Wildcat Ranch		Bolema Club	37°58'13" 122°47'18"
Wilkins	McCurdy		37°56'11" 122°41'54"

A NOTE ON THE GEOLOGIC MAP

(omitted from the online edition)

The geologic map was prepared by the writer using as a base the five 7-1/2—minute U.S. Geological Survey topographic quadrangles that cover the area. The mapping was done entirely on foot, using vertical aerial photographs of series GS—UX (1952) to determine and record the locations of the nearly 1500 observations.

Most of the area is thickly covered with chaparral or forest, and long continuous outcrops are rare. The geologic map, like most geologic maps, is interpretative, displaying the author's conclusions as to the geology based on his actual observations.

Dips of the beds are shown to the nearest 5 degrees. Only selected attitudes are shown in order to avoid confusion and clutter on the map.

The boundary between the predominant claystones and siltstones of the Drakes Bay Formation and the basal sandy facies of the same formation is not a sharp line as drawn on the map but is definitely gradational. However, the distinction between the two types of rock is important and is shown on the map although the line itself does not properly represent the gradational nature of the transition.

SUGGESTIONS FOR FUTURE RESEARCH

There are still many unanswered questions about the geology of Point Reyes Peninsula. The following are some suggestions for further study:

(1) Search the metamorphic limestones for fossils, such as crinoid plates or siliceous organisms.

(2) Make a detailed petrologic study of granitic rocks.

(3) Determine the provenance of the Franciscan tectonic inclusions of the San Andreas fault zone.

(4) Analyze the rocks of the Paleocene conglomerate and compare with rocks from Cordell Bank, Sugar Loaf Rock on the Farallon Islands, and the Carmelo Formation.

(5) Study the foraminiferal succession of the Miocene rocks.

(6) Study the fossils and mineralogy of the glauconite bed, and the fossils of the shales, of the Drakes Bay Formation.

(7) Geomorphic study of (a) the marine terraces and high-level peneplane and their interrelationships, (b) the topographic features of the fault zone, (c) erosional rate of sea cliffs, and (d) the development of Bear Valley and Pine Gulch Creek.

(8) Geochronologic study of the K—Ar dates of granitic rocks of Point Reyes, Point Tomales, Bodega Head, and Cordell Bank.

(9) Using shallow seismic methods, study the submarine connections between Point Reyes Peninsula and adjacent sections of the San Andreas fault zone.

REFERENCES CITED

Anderson, C.A., 1963, Simplicity in structural geology, *in* Albritton, C.C. Jr., editor, The fabric of geology, Reading, Massachusetts, Palo Alto, London, Addison—Wesley Publishing Company, Inc., 372 p.

Anderson, F.M., 1899, The geology of Point Reyes Peninsula, University of California Publications, Bulletin Department of Geology, v. 2, no. 5, p. 119-153.

Axelrod, D.I., 1967, Evolution of the Californian closed-cone pine forest, *in* Sympasium on the biology of the California Islands, Proceedings, Santa Barbara Botanical Garden, 1965.

Bailey, E.H., Irwin, W.P., and Jones, D.L., 1964, Franciscan and related rocks and their significance in the geology of western California, California Division of Mines and Geology Bulletin 183.

Berggreen, W.A., 1969, Rates of evolution in same Cenozoic planktonic Foraminifera: Micropaleontology, v. 15, no. 3, p. 351-365.

Berry, F.A.F., Huffman, O.F., and Turner, D.L, 1966, Post-Miocene movement along the San Andreas fault, California, Geological Society of America, Annual Meetings, San Francisco, November 14-16, 1966, Abstracts with Program, p. 15-16.

Bingham, Helen, 1906, In Tomal land: San Francisco, Calkins Publishing House.

Blake, W.P., 1856, Geology of Punto de Los Reyes, *in* Report of the Superintendent of the U.S. Coast Survey for 1855, Geological Report No. 65, Western Coast, p. 386: U.S. Senate, 34th Congress, 1st session, Ex. Doc. No. 22.

Blake, W.P., 1856, Notice of remarkable strata containing the remains of *Infusoria* and *Polythalamia* in the Tertiary Formation of Monterey, California: Academy of Natural Sciences, Philadelphia, Proceedings, v. 7, 1854-55 (1856) p. 328-331.

Bowen, O.E. Jr., 1951, Highways and byways of particular geologic interest, *in* Geologic guidebook of the San Francisco Bay counties: California Division of Mines Bulletin 154, p. 315-379.

Bowen, O.E. Jr., 1965, Stratigraphy, structure, and oil possibilities in Monterey and Salinas quadrangles: Pacific Section American Association of Petroleum Geologists Fortieth Annual Convention, Bakersfield, California, A symposium of papers, p. 48-67 (19661.

Bradley, W.C., and Addicott, W.O., 1968, Age of first marine terrace near Santa Cruz, California, Geological Society of America Bulletin, v. 79, p. 1203-1210.

Bradley, W.W., 1916, The counties of Colusa, Glenn, Lake, Marin, Napa, Solano, Sonoma, Yolo: California State Mining Bureau Fourteenth Report of the State Mineralogist, p. 173-370.

Bramlette, M.N., 1946, The Monterey Formation of California and the origin of its siliceous rocks: U.S. Geological Survey Professional Paper 212.

Bowen, O.E., Jr., and Gray, C.H., Jr., 1959, Limestone and dolomite in the northern Gabilon Range, California: California Division of Mines Special Report 56, 40 p.

Brewer, W.H., 1930. Up and down California in 1860-1864: Yale University Press, New Haven, 601 p.

Brooks, K.G., 1965, Natural gamma aeroradio-activity map of parts of the San Francisco region, California: U.S. Geological Survey Geophysical Investigations Map GP—483.

Brown, R.D. Jr., 1967, Most conspicuous strands of the San Andreas and related faults, southwestern Marin County, California; A contribution of the National Center for Earthquake Research: U.S. Geological Survey Open File Report.

Chapman, R.H., 1966, The gravity field in northern California. *in* Bailey, E.H., editor, Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 395-405.

Chapman, R.H., and Bishop, C.C., 1968, Bouguer gravity map of California, San Francisco sheet: California Division of Mines and Geology, scale 1:250,000.

Cherry, J.A., 1964, Sand movement along a portion of the northern California coast: Hydraulic Engineering Laboratory, University of California, Berkeley. Technical Report Series, HEL—4—3.

Chesterman, C.W., 1952, Descriptive petrography of rocks dredged off the coast of central California: California Academy of Science, Proceedings, 4th Series, v. 27, no. 10.

Clague, J.J., 1969, The landslides in the southeast part of Point Reyes National Seashore: M.A. thesis, University of, California, Berkeley.

Clark, J.C., 1966, Tertiary stratigraphy of the Felton-Santa Cruz area, Santa Cruz Mountains, California: Stanford University, unpublished Ph.D. thesis.

Clement, W.G., 1965, Complete Bouguer gravity map of the northern part of the San Francisco Bay area and its geologic interpretation: U.S. Geological Survey Geophysical Investigations Map GP—468.

Compton, R.R., 1966, Granitic and metamorphic rocks of the Solinian Block, California Coast Ranges, *in* Bailey, E.H., editor, Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 277-287.

Cooper, W.S., 1967, Coastal dunes of California: Geological Society of America Memoir 104, 131 p.

Crawford, J.J., 1896, Thirteenth Report of the State Mineralogist, California State Mining Bureau.

Crowell, J.C., 1962, Displacement along the San Andreas fault, California: Geological Society of America Special Paper 71.

Cummings, J.C., Touring, R.M., and Brabb, E.E., 1962, Geology of the northern Santo Cruz Mountains. California, *in* Geologic guide to the gas and oil fields of northern California, California Division of Mines and Geology Bulletin 181, p. 179-220.

Curray, J.R., 1965, Late Quaternary history, continental shelves of the United States, *in* The Quaternary of the United States: Princeton, New Jersey, Princeton University Press, p. 723-735.

Curtis, G.H., Evernden, J.F., and Lipton, J., 1958. Age determination of some granitic racks in California by the potassium-argon method: California Division of Mines Special Report 54.

Daetwyler, C.C. Jr., 1965, Marine geology of Tomales Bay, central California, Ph.D. thesis, University of California, San Diego.

Dale, R.H., and Rantz, S.E., 1966, Hydrologic reconnaissance of Point Reyes National Seashore area, California, U.S. Geological Survey Open File Report.

Darrow, R.L., 1963, Age and structural relationships of the Franciscan Formation in the Montara Mountain quadrangle: California Division of Mines and Geology Special Report 78, 23 p.

Dickerson, R.E., 1922, Tertiary and Quaternary history of the Petoluma, Point Reyes and Santa Rosa quadrangles: California Academy of Science Proceedings, 4th Series, v. 11, no. 19, p. 527-601, pls. 17-41.

Dickert, P.F., 1966, Tertiary phosphatic facies of the Coast Ranges, *in* Bailey, E.H., editor, Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 289-304.

Dickinson, W.R., and Grantz, Arthur, editors, 1968, Proceedings of conference on geologic problems of San Andreas fault system: Stanford University Publications, Geological Sciences, v. 11, 374 p.

Douglas, J.M., 1943, Duxbury Point region, *in* Geologic formations and economic development of the oil and gas fields of California, California Division of Mines Bulletin 118, p. 621.

Douglas, J.M., and Rhoades, R.S., 1915, Geology of Point Reyes Peninsula: Undergradute thesis, University of California, Berkeley.

Durst, F.M., 1915, Identification and correlation of marine terraces of the California coast between Santa Cruz and Bolinas, M.A. thesis, University of California, Berkeley.

Eckel, E.C., 1933, Limestone deposits of the San Francisco region: California Journal of Mines and Geology, v. 29, p. 348-361.

Emery, K.O., 1960, The sea off southern California: New York, London, John Wiley & Sons, 366 p.

Fairbridge, R.W., 1960, The changing level of the sea, Scientific American, May.

Fitch, A.A., 1931, The geology of Ben Lomond Mountain: University of California Publications in Geological Sciences, v. 21, no. 1, p. 1-13.

Galloway, A.J., 1961, The geology of the Point Reyes Peninsula, *in* Land use survey, proposed Point Reyes National Seashore, San Francisco; National Park Service Region 4, p. 30-34 and map.

Galloway, A.J., 1962, Field trip 3. Point Reyes Peninsula and San Andreas fault zone, *in* Bowen, O.E. Jr., editor, Geologic guide to the gas and oil fields of northern California: California Division of Mines and Geology Bulletin 181, p. 391-398, p. 26.

Galloway, A.J., 1966, Field trip to Point Reyes Peninsula and San Andreas fault zone, *in* Bailey. E.H., editor, Geology of northern California: California Divition of Mines and Geology Bulletin 190, p. 429-440.

Gilbert, G.K., 1908, Characteristics of the rift and Earth movement on the fault, Tomales Bay to Bolinas Lagoon *in* Report of the State Earthquake Investigation Commission: Carnegie Institution of Washington Publication 87, v. 1, Pt. 1, p. 30-35, 66-87.

Glen, William, 1959, Pliocene and lower Pleistocene of the western part of the San Francisco Peninsula, University of California Publications, Geological Sciences, v. 36, no. 2. p. 147-198.

Gluskoter, H.J., 1962, Geology of a portion of western Marin County: Ph.D. thesis, University of California, Berkeley.

Gluskoter, H.J., 1969, Geology of a portion of western Marin County, California: California Division of Mines and Geology Map Sheet 11.

Gower, H.D., and Madsen, B.M., 1964, The occurrence of phosphate rock in California: U.S. Geological Survey Professional Paper 501—D, p. D79-D85.

Griscom, Andrew, 1966, Magnetic data and regional structure in northern California, *in* Bailey, E.H., editor, Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 407-417.

Hanna, G D., 1952, Geology of the continental slope off central California: California Academy of Science, Proceedings, 4th Series, v. 27, no. 9, p. 325.

Higgins, C.G., 1961, San Andreas fault north of San Francisco. California: Geological Society of America Bulletin, v. 72, p. 51-68, 1 pl.

Holway, R.S., 1914, The effect of seven years erosion on the California fault line of 1906: American Geographic Society Bulletin, v. 46, no. 6. p. 420-426.

Hoskins, C.W., 1957, Paleoecology and correlation of the lowest emergent marine terrace, from San Clemente to Halfmoon Bay: Ph.D. thesis, Stanford University.

Howell, J.T., 1949, Marin flora, University of California Press, 319 p.

Irelan, William Jr., 1888, Seventh annual report of State Mineralogist for the year ending October 1, 1887: California State Mining Bureau.

Irelan, William Jr., 1888, Eighth annual report of the State Mineralogist for the year ending May 15, 1888: California State Mining Bureau.

Johnson, R.G., 1962, Mode of formation of marine fossil assemblages of the Pleistocene Millerton Formation of California: Geological Society of America Bulletin, v. 73, p. 113-130.

Jones, R.B., 1963, A geophysical interpretation of on offshore gravity survey near San Francisco [Abstract]: American Geophysical Union Transactions, v. 44, no. 1, p. 32.

Kistler, R.W., Bateman, P.C., and Brannock, W.W., 1963, Isotopic ages of minerals from granitic rocks of the east-central Sierra Nevada and Inyo Mountains, California: Geological Society of America Annual Meeting. Proceedings, New York, p. 91A.

Kleinpell, R.M., 1938, Miocene stratigraphy of California: Tulsa, Oklahoma, American Association of Petroleum Geologists, 450 p.

Koenig, J.B., 1962, Index to geologic maps of California, 1957-1960: California Division of Mines and Geology Special Report 52A.

Koenig, J.B., and Kiessling, E.W., 1968, Index to geologic maps of California, 1961-1964: California Division of Mines and Geology Special Report 52B.

Lattman, L.H., 1958, Technique of mapping geologic fracture traces and lineaments an aerial photographs: Photogrammetric Engineering, v. 24, no. 4.

Lawson, A.C., 1894, The geomorphogeny of the coast of northern California: University of California, Bulletin Deportment of Geology, v. 1, no. 8. p. 241-271.

Lawson, A.C., and others, 1908, The California earthquake of April 18, 1906, Report of State Earthquake Investigation Commission: Carnegie Institution of Washington Publication 87, v. 1, atlas.

Lawson, A.C., 1914, Description of the San Francisco (California) district: U.S. Geological Survey, Geologic Atlas, Folio 193.

Marin Journal, 1865, March 25 issue, Petroleum at Bolinas.

Marin Journal, 1875, November 18 issue, Coal at Olema.

Marin Journal, 1893, January 5 issue, Gas at Duxbury Point.

Martin, B., 1914. Descriptions of new species of fossil mollusca from the later marine Neocene of California, University of California Publications, Bulletin of the Department of Geology, v. 8, no. 7, p. 181-202.

Martin, B., 1916, The Pliocene of middle and northern California, University of California Publications, Bulletin of the Department of Geology, v. 9, no. 15, p. 215-259.

Mason, H.L., 1934, Pleistocene flora of Tamales Formation, Carnegie Institution of Washington Publication 415, p. 81-179.

Minard, C.R. Jr., 1964, The erosional and depositional history of the coast of northern California: University of California Hydraulic Engineering Laboratory Technical Report no. HEL—2—10.

Munro—Fraser, J.P., 1880, History of Marin County: San Francisco, Alley, Bowen and Company.

Noble, L.F., 1926, The San Andreas rift and some other active faults in the desert region of southeastern California, Carnegie Institution of Washington Yearbook 25, p. 415-428.

Oakeshatt, G.B., 1966, San Andreas fault in the California Coast Ranges Province, *in* Bailey, E.H., editor, Geology of northern California: California Division of Mines and Geology Bulletin 190. p. 357-373.

Page, B.M., 1966, Geology of the Coast Ranges of California, *in* Bailey, E.H., editor, Geology of northern California: California Division of Mines and Geology Bulletin 190, p. 255-275.

Parker, E.W., 1893, Coal, *in* Mineral resources of the United States: U.S. Geological Survey, 1893, p. 214.

Petaluma Journal and Argus, 1868, February 15 issue.

Reed, R.D., 1933, Geology of California, Tulsa, Oklahoma, American Association of Petroleum Geologists, 355 p.

Richards, H.G., and Thurber, D.L., 1966, Pleistocene age determination from California and Oregon: Science, v. 152, p. 1091.

St. Amant, ES., 1905, Duxbury gas seep: Scientific American, April 15.

Schlocker, Julius, and Bonilla, M.G., 1962, Field trip 4, San Francisco Peninsula, *in* Bowen, O.E. Jr., editor, Geologic guide to the gas and oil fields of northern California: California Division of Mines and Geology Bulletin 181.

Sharp, R.P., 1954, Physiographic features of faulting in southern California, *in* Johns, R.H., editor, Geology of southern California: California Division of Mines Bulletin 170, Chapter 5, p. 23.

Spotts, J.H., 1962, Zircon and other accessory minerals, Coast Range batholith, California: Geological Society of America, v. 73, p. 1221-1240.

Strand, R.G., Koenig, J.B., and Jennings, C.W., 1958, Index to geologic maps of California to December 31, 1956: California Division of Mines Special Report 52.

Taliaferro, N.L., 1934, Contraction phenomena in cherts, Geological Society of America Bulletin, v. 45, no. 2, p. 189-232.

Taliaferro, N.L., 1951. Geology of the San Francisco Bay counties, *in* Geologic guidebook of the San Francisco Bay counties: California Division of Mines Bulletin 154, p. 117-150.

Thalmann, H.E., 1943, Upper Cretaceous Age of the "Franciscan" Limestone near Laytonville, Mendocino County, California [abstract]: Geological Society of America Bulletin, v. 54, no. 12, p. 1827.

Trask, J.B., 1856, Report on the geology of northern and southern California: State Geologists Fourth Annual Report.

Trask, P.D., 1926, Geology of the Point Sur quadrangle. California, University of California Publications, Bulletin of the Department of Geology, v. 16, p. 119-234.

Treganza, A.E., 1951, Old lime kilns near Olema. *in* Geologic guidebook of the San Francisco Bay counties: California Division of Mines Bulletin 154, p. 65-72.

Vander Leck, Lawrence, 1921, Petroleum resources of California with special reference to unimproved areas, California Mining Bureau Bulletin 89, p. 35-36.

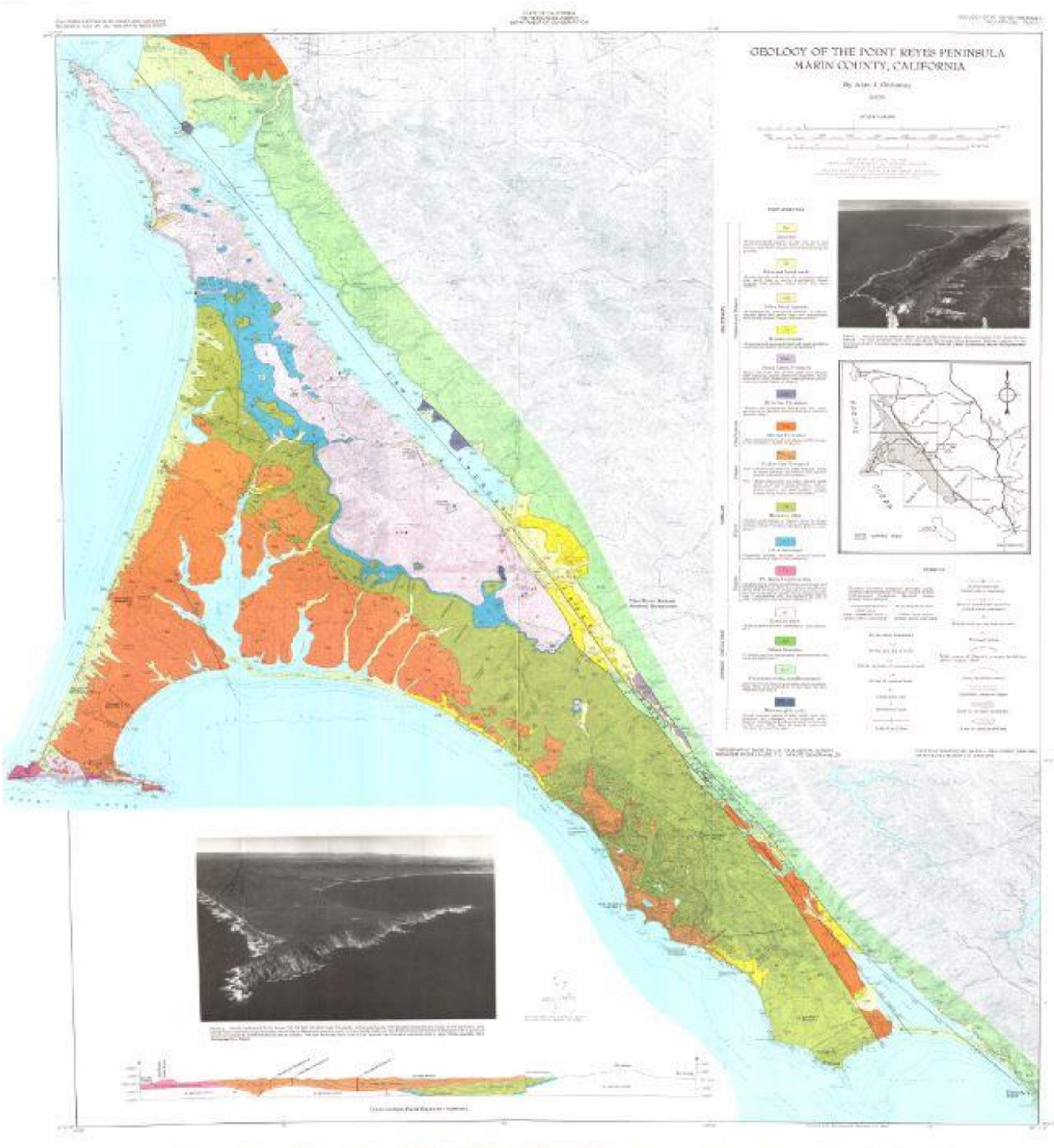
Ver Planck, W.E., 1955, Mines, mineral resources, and mineral industries of Marin County, California: California Journal of Mines and Geology, v. 51, no. 3, p. 221-289.

Watts, W.L., 1893, Marin County. *in* Eleventh report of the State Mineralogist. 1891-1892: California Mining Bureau, p. 251.

Weaver, C.E., 1949a, Geology of the Coast Ranges immediately north of the San Francisco Bay region, California, Geological Society of America Memoir 35.

Weaver, C.E., 1949b, Geology and mineral deposits of an area north of San Francisco Bay: California Division of Mines Bulletin 149, 135 p.

Whitney, J.D., 1865, Geological Survey of California, Geology, v. 1, p. 84-85.



Click HERE to view/download higher resolution map