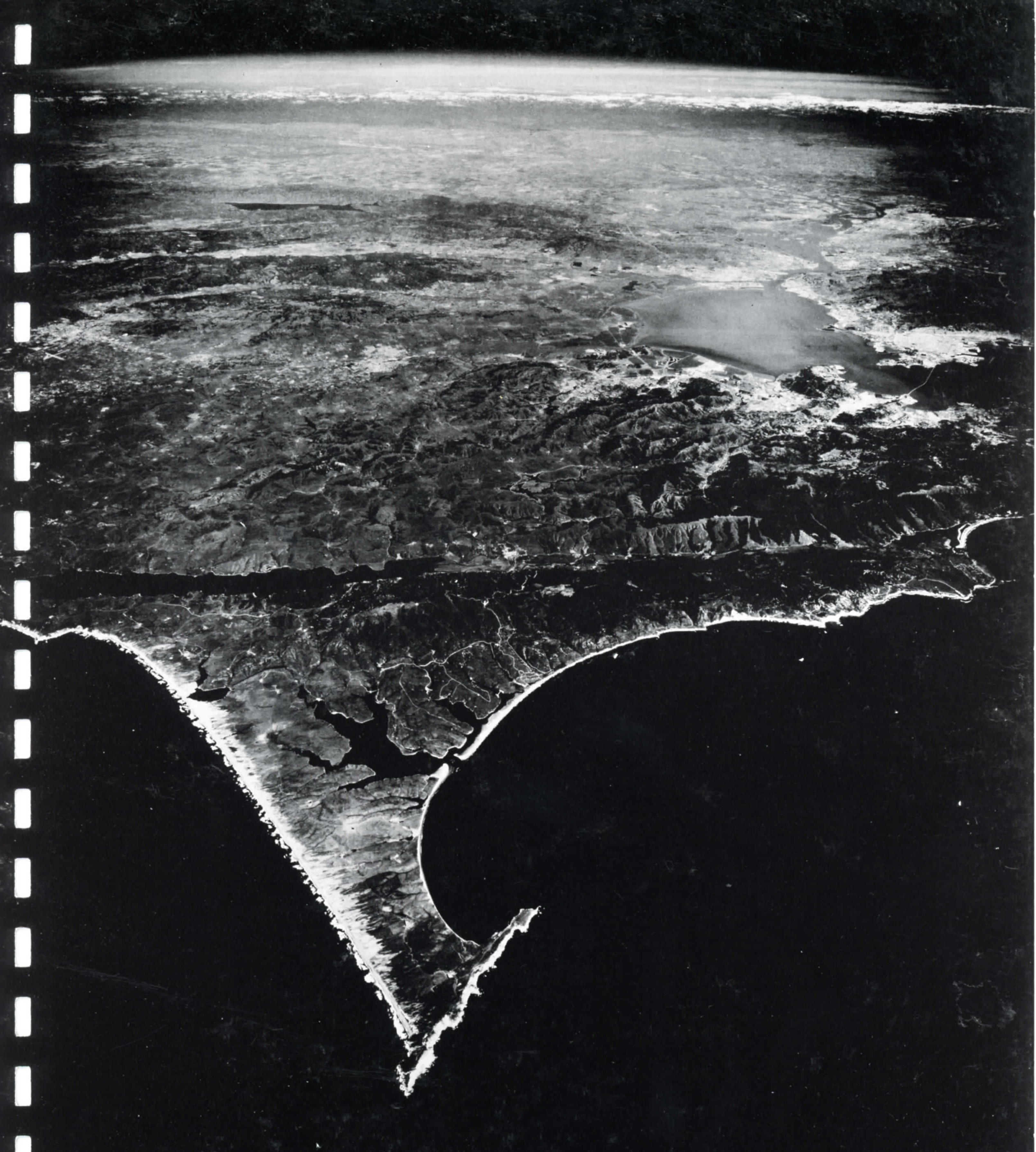
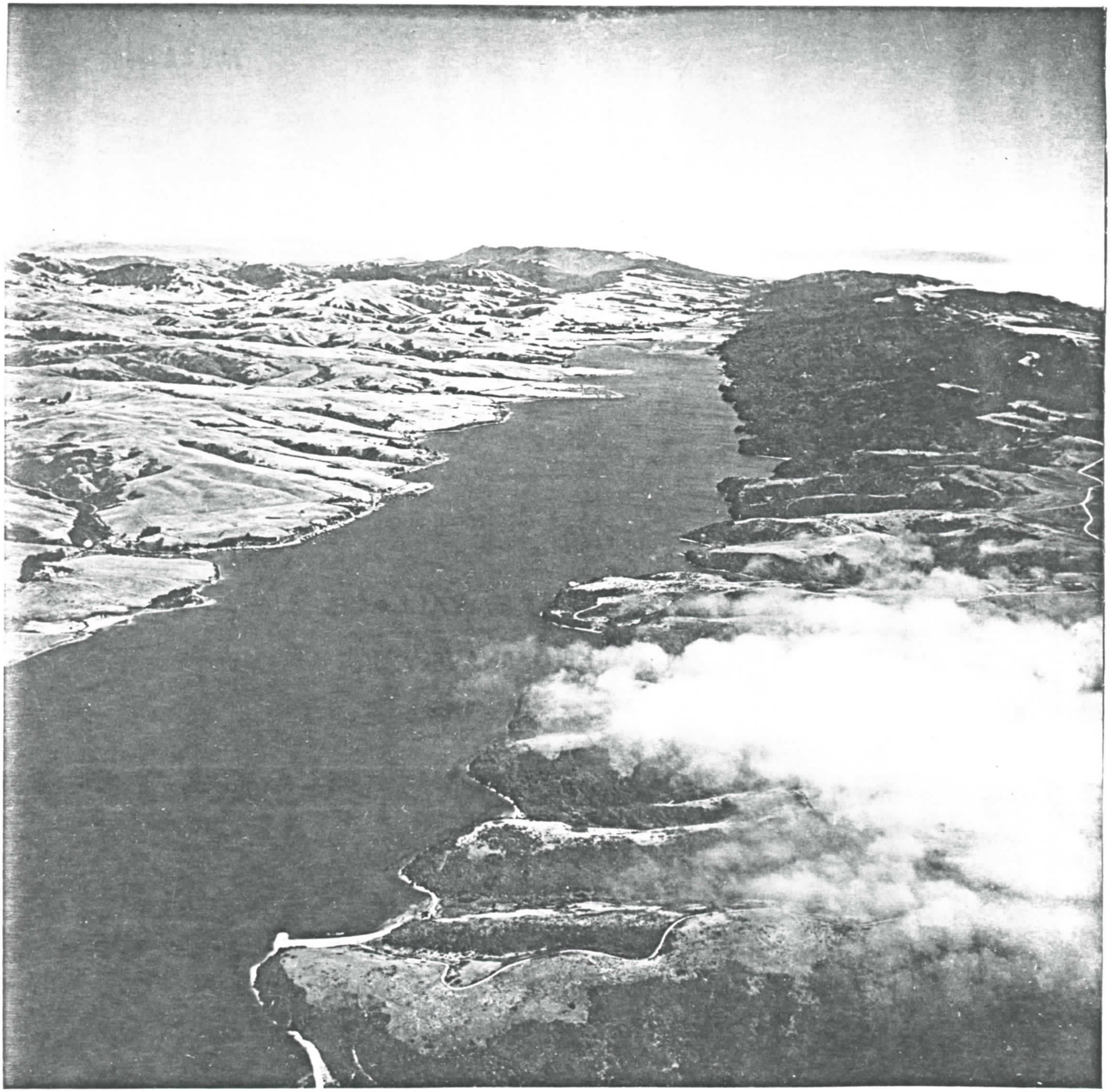


GEOLOGIC GUIDEBOOK TO POINT REYES

Northern California Geological Society



Frontispiece. Aerial photograph of Tomales Bay looking south. Courtesy US Geological Survey.

GEOLOGIC GUIDEBOOK

TO THE

POINT REYES AREA,

NORTHERN CALIFORNIA

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Prepared for the Spring 1989 field trip
of the Northern California Geological Society

Cover Photo: Point Reyes from 60,000 ft. Courtesy US Geological Survey

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ACKNOWLEDGMENTS

A considerable portion of the geology discussed in this guidebook came from a limited number of sources. Perhaps the most heavily relied upon were Clark and others (1984), Galloway (1977), and Blake and others (1974). Historical and cultural references in the road log were gleaned from Gudde (1969) and Teather (1986).

This field guide is the result of the hard work put in by the contributors listed on the title page and other members of the field trip committee. Tom MacKinnon helped with the geologic maps and edited the Franciscan sections. Shawn May handled all the photographic work, and is to be commended for the cover. Linda Thurn and Deborah Wechsler organized the refreshments and audio-visual equipment for the field trip. Juan Guerrero handled the finances and getting us transportation and lunch. Jason Donchin, Gordon Manings and others too many to mention gave ideas, logistical help, and otherwise gave up their free time to help put the trip and guidebook together. The editor thanks all of these people for their efforts. Valuable assistance was also provided by the National Park Service at Point Reyes.

Corporate sponsorship was provided by Chevron in the form of word processing and reproduction of the guidebooks. Chevron's continual support of NCGS field trips is invaluable and is one of the main factors that allows NCGS to publish guidebooks at all. All of the members of NCGS deeply appreciate Chevron's support.

Sponsorship was also provided by the Terra Linda Group in the form of liquid refreshments for the day of the trip. We thank them for their support and the generous budget which supplied us with a wonderful selection of beer.

FOREWORD

The purpose of this field trip guidebook is to introduce the geologist to the geology of Point Reyes Peninsula and its relation to the rest of California. The outcrops visible in the Point Reyes area are significant for the geological interpretation of a considerable portion of western California. Some excellent exposures of Franciscan are easily accessible and outcrops of granitic basement and overlying sediment are particularly well exposed. The types of rocks exposed on the Point Reyes Peninsula dominate the offshore basins between Cape Mendocino and San Francisco.

The guidebook is written for geologists but will also prove interesting reading for non-geologists as well. Geology can get pretty dry at times, especially when faced with an abundance of beautiful scenery, so there are many references to historical, biological, and geographical points of interest in the roadlog. There are many more places of interest to visit in the Point Reyes area than those described in this guidebook. Some of the most interesting include the Point Reyes lighthouse, Limantour Beach, Bodega Bay, and Bolinas.

The trip is meant to last one day, but with some sightseeing or in-depth geologic study it may be stretched out to a 2-day trip. There is no lack of places to camp or stay in the Point Reyes area. Camping is available at Point Reyes National Seashore, in 4 hike-in campgrounds. Nearby car camping is available at Samuel Taylor State Park (60 sites, 2 group sites), Mt. Tamalpais State Park (15 tent sites), and Doran County Park in Bodega Bay (128 trailer sites, 9 tent sites). Overnight lodging, which can be fairly quaint, is available at Inverness, Pt. Reyes Station, and Bodega Bay.

One last note. The stops visited on this trip are classic localities and most of them are in a National Park. Rock collecting can only be done with a permit. Please refrain from sampling any of the outcrops.

HOW TO USE THIS GUIDEBOOK

Many of the geologic guidebooks to the Point Reyes published in the recent past have been more a collection of papers than true guidebooks. In the interests of publishing a guide which can be followed and enjoyed throughout the length of a trip, without continual thumbing back and forth to the roadlog, I have combined much of the text and the roadlog using the style of the ESSSO guidebooks of the Earth and Space Sciences Department at UCLA.

The road log is set off from the rest of the text by indentation and important driving instructions are underlined. Individual stops and their explanatory material are imbedded in the roadlog as a sort of script to follow during the field trip. Mileage relative to certain cultural features is used to point out items of interest. Please be sure to note your mileage at these points. A route map is included on page xxvi to help with navigation.

Small-scale geologic maps are included on pages xii and xv to help the reader understand the geology of the Point Reyes area. Large-scale maps of the stops are also provided. Other published maps may be helpful. Geologic maps of the 1:250,000 scale Santa Rosa and San Francisco Sheets by the California Division of Mines and Geology are useful to inspect before and during the trip. Larger scale geologic maps are also available by Blake and others (1974), Gluskoter (1969), and Galloway (1977). Strip maps of the San Andreas Fault zone published by Brown and Wolfe (1972) are a valuable guide to fault features in Olema Valley.

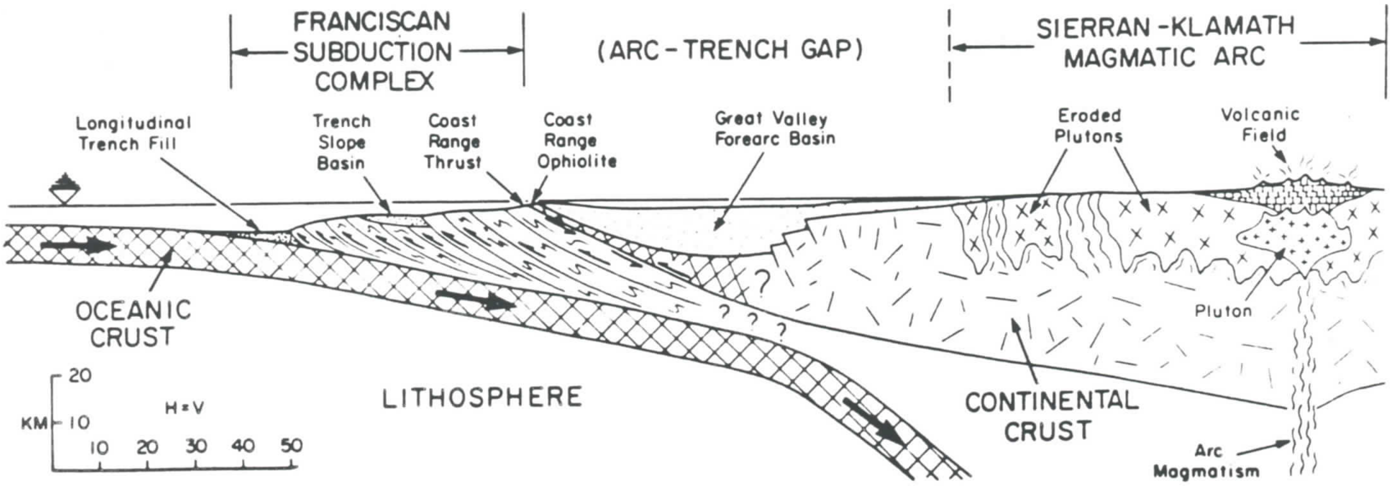


Figure 1. Tectonic cross-section of western margin of California during Late Cretaceous/Early Paleogene (from Dickinson and others, 1982).

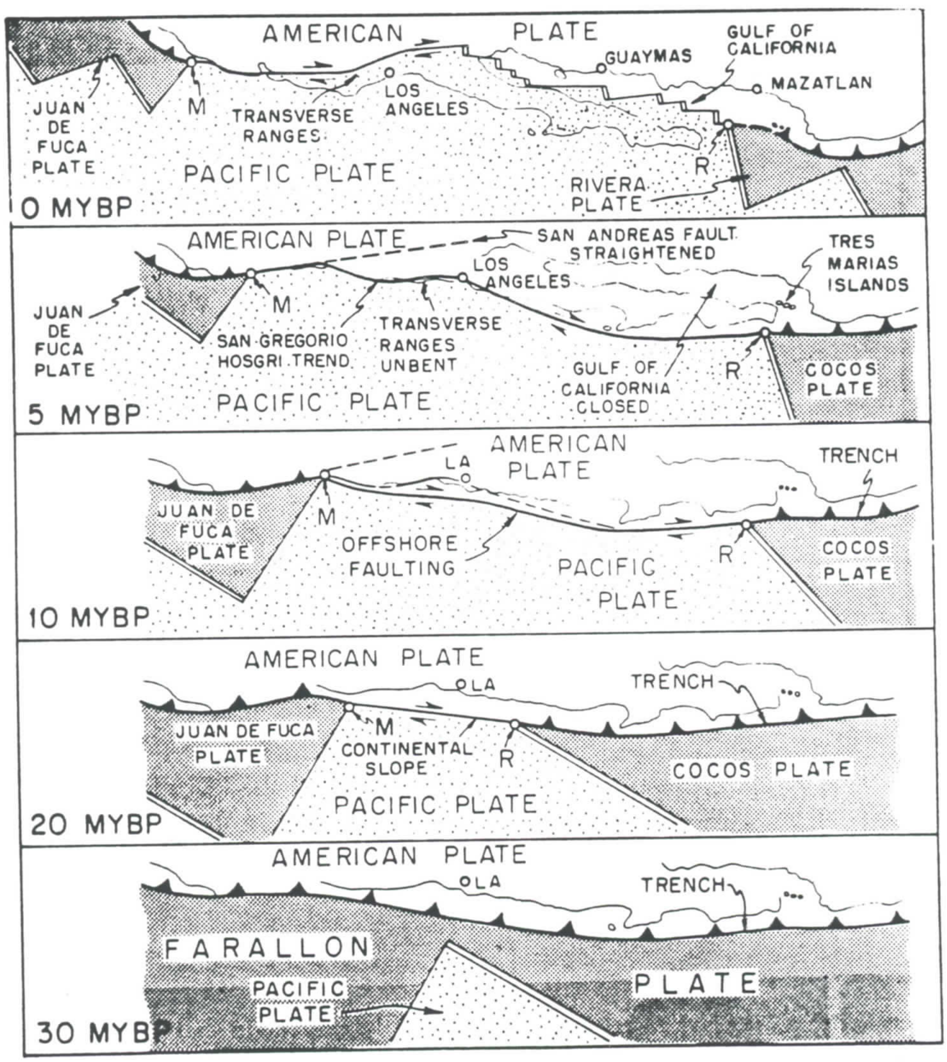


Figure 2. Sequential Neogene evolution of western margin of California (from Dickinson, 1981).

A BRIEF TECTONIC HISTORY OF WESTERN CALIFORNIA

The geologic history of the Point Reyes area starts in the Mesozoic, about 150 million years ago in the Late Jurassic Era. At that time the oceanic crust west of California, the Farallon plate, was being subducted beneath the overriding North American continent in a setting similar to the west coast of South America today (see Figure 1). The Great Valley sequence, now occupying the Sacramento Valley, was being deposited in the so-called fore-arc basin between the continental arc volcanics on the east (the Sierra Nevada) and the offshore trench on the west. At the same time, the Franciscan assemblage was developing in the wedge zone between the downgoing oceanic Farallon plate and the fore-arc basin.

With time the continent began to overtake the East Pacific Rise, the spreading center between the Pacific and Farallon plates. Apparently, the thin oceanic crust in the young Farallon plate did not subduct as readily as the cooler, heavier, older crust. The plate's relative buoyancy caused it to subduct at a much shallower angle, riding just beneath the continent (Dickinson, 1981). The shallow subduction may have slowed melting of the oceanic plate, causing the cessation of arc volcanism and plutonism in the Sierra Nevada. In addition, the shallow subduction seems to have been responsible for the Laramide orogeny in the Rocky Mountains during the Paleogene.

At about 29 million years ago the continent overrode the East Pacific Rise (Atwater, 1970). Because the oceanic plate was no longer being subducted, a transform fault formed at the junction between the Pacific and North American plates, linking the remaining subduction zones to the northwest and southeast (see Figure 2). This transform fault, the active part now known as the San Andreas fault, grew with time and appears to have stepped continent-ward since its inception. Since then the fault has dominated the structural evolution of most of western California.

Well-documented displacement on the San Andreas fault system amounts to 305 km in northern California since the Early Miocene (ca. 23 mybp, Clark and others, 1984) and 330 km in southern California since the Late Miocene (8 mybp, Crowell, 1981). Other faults west of the San Andreas, such as the San Gregorio or Hosgri faults, have also apparently taken up some slip between the plates during the same time period. Little is known about these other faults because most of their lengths are located offshore. Clark and others (1984) documented about 150 km of slip on the San Gregorio fault just south of Point Reyes (Figure 3), giving a total slip in northern California of 455 km.

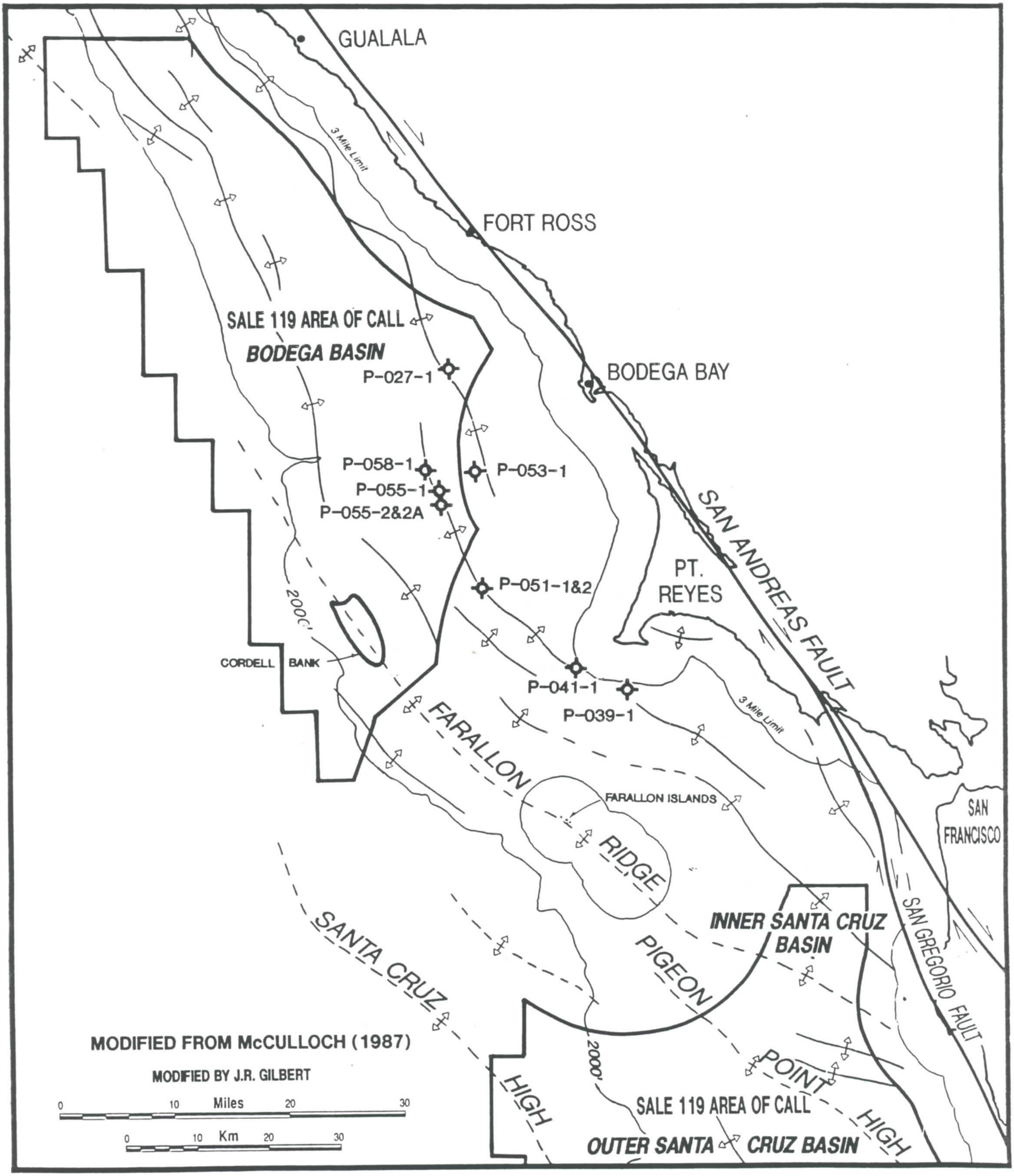


Figure 3. Regional geologic map of coastal and offshore California.

GEOLOGY OF POINT REYES PENINSULA

On a geologic map of northern California, the Point Reyes Peninsula sticks out as something quite different from the rest of the nearby coastal rocks. The primary reason for this is that the peninsula, separated from the rest of California by the San Andreas fault, is underlain by granitic crust whereas the area east of the fault is underlain by Franciscan assemblage rocks derived from oceanic crust. How Point Reyes came to be where it is today is an interesting story and is still being studied. Many of the interpretations are controversial and provide some of the more fascinating stories in the tectonic development of California.

The following section is a general description of the rocks found at Point Reyes which can be referred to while visiting any part of the peninsula. Refer to the geologic map on Figure 4 to locate the outcrops. Following the general description is a short discussion of the origin of Point Reyes and the Salinian block. Much of this section was abstracted from Clark, et al., 1984.

Granitic Basement

The Point Reyes Peninsula is underlain by Cretaceous granitic basement similar to Sierra Nevada batholithic rocks. The peninsula is considered to be part of Salinia, a sliver of continental crust sandwiched between the San Andreas fault on the east and the Sur-Nacimiento fault on the west. The granite ranges from porphyritic granodiorite to tonalite in composition and is exposed on the northern part of Inverness Ridge and at Point Reyes. The rocks have been radiometrically dated and Ross (1978) concluded they are approximately 100 m.y. old. We will have the opportunity to examine excellent exposures of these rocks at Kehoe Beach.

Metamorphosed sedimentary rocks occur within the granite as roof pendants or septa. These mica schists, quartzites, and marbles represent the oldest rocks in the Point Reyes area. Correlated by Weaver (1949) with the Sur Series exposed in Santa Lucia Range near Big Sur, they may be remnants of the platform sediments which were deposited off the western coast of the continent during the Paleozoic.

Tertiary Sediments

Deposited on top of the eroded surface of the granite basement is up to 4370 meters of Tertiary sedimentary rocks. The rocks appear to be little deformed, except for contorted portions of the Monterey Formation, and are folded into a broad syncline (see Figure 5). The rocks range in age from Eocene to Pliocene and were deposited in a marine environment.

Point Reyes Conglomerate. The oldest Tertiary sediments exposed on the peninsula are the conglomerates and sandstones of the Point Reyes

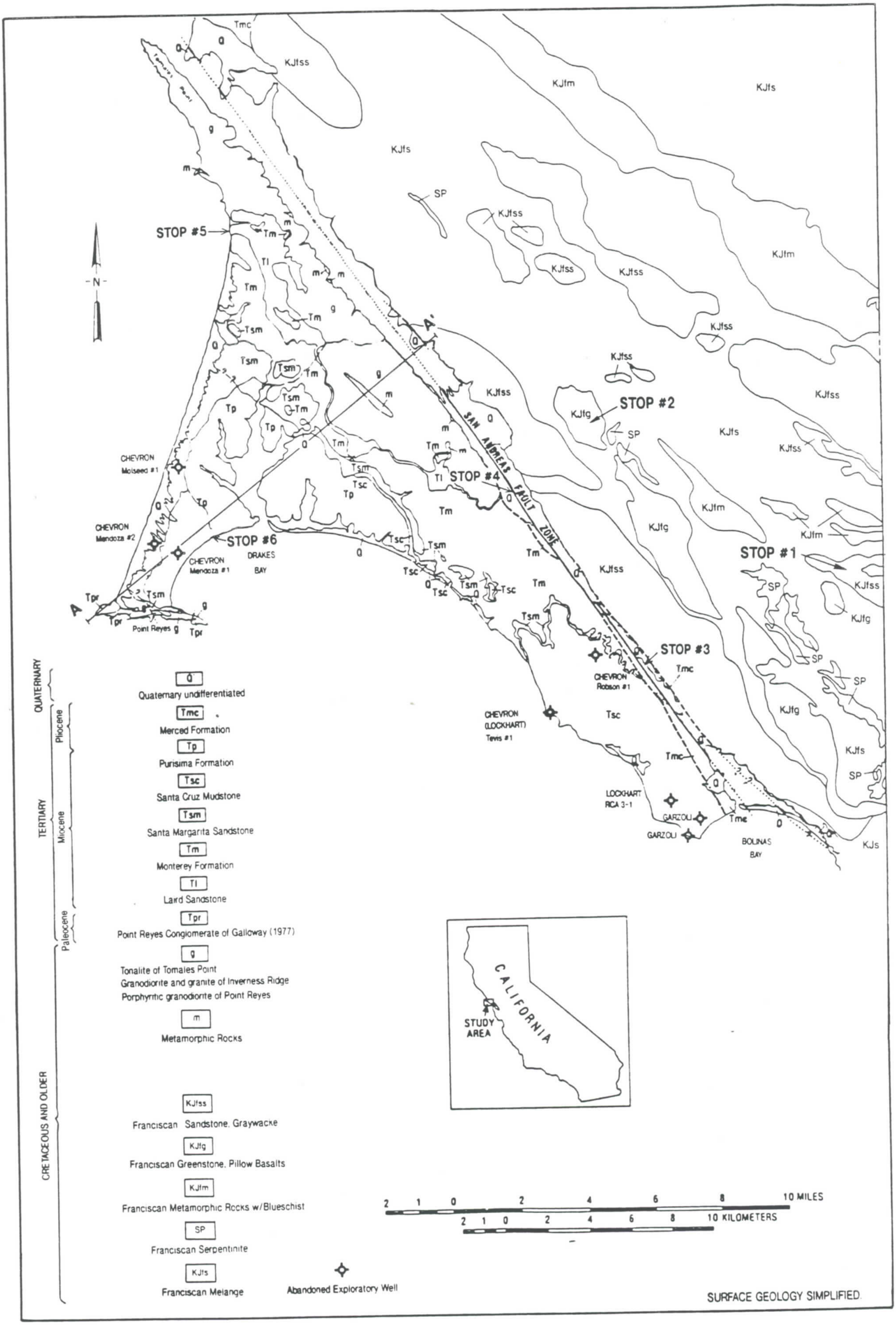
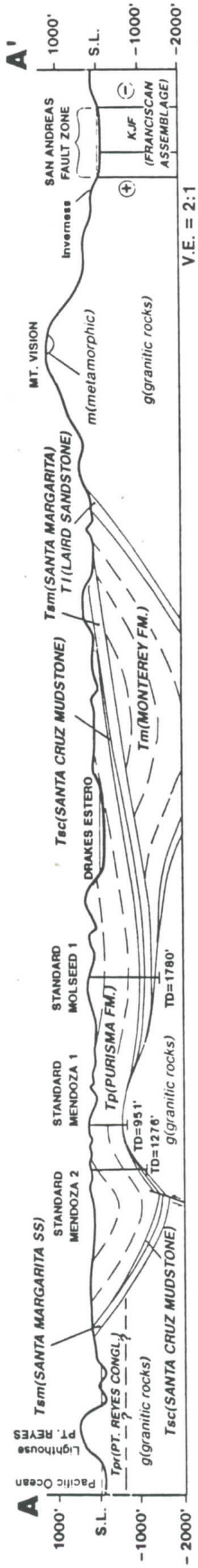


Figure 4. Geologic map of the Point Reyes area (modified from Clark and others, 1984; and Blake and others, 1974).



CROSS SECTION POINT REYES TO MILLERTON

(MODIFIED FROM GALLOWAY (1976) AND CLARK AND OTHERS (1984)

(MODIFIED BY T.C. MACKINNON AND J.R. GILBERT)

Figure 5. Structural cross-section through the Point Reyes area.

Conglomerate (Galloway, 1977). Deposited directly on the granite, the conglomerate is only exposed on Point Reyes itself where it is about 210 meters thick. Clasts in the conglomerate are mainly well rounded and are as large as 2 to 3 meters. Most of the clasts are granodiorite and purple and black porphyritic siliceous volcanics. Also present are quartzite, red chert, and black and green volcanics. Because of the lack of an exposure of the volcanics nearby, one can only speculate on their source. The limited exposure of the conglomerate, northwest-directed paleocurrent indicators, and bathyal fauna in siltstone rip-up clasts suggest that the conglomerate was deposited in a mid-channel setting in a submarine fan. Unfortunately, because of the conglomerate's limited exposure we will not have the time to examine it on this trip.

Laird Sandstone. The Laird Sandstone is a transgressive sand deposited on the granite at most exposures on the peninsula. Up to about 60 meters thick, the sand probably was derived mostly from the underlying granite. It has been dated as Luisian (Middle Miocene) from foraminifers in the base of the overlying Monterey Formation. We will see an excellent exposure of the Laird Sandstone at our Kehoe Beach stop.

Monterey Formation. About 1050 to 1500 meters of siliceous mudstone, porcelanite, chert, and shale of the Monterey Formation lie conformably on the Laird. The Monterey has been dated as Luisian to Mohnian (Mid to Late Miocene) from benthic forams. The sediments comprise some of the more highly deformed rocks on the Point Reyes Peninsula; however, much of that deformation may have occurred shortly after deposition and may not be the result of tectonic stresses. The Monterey is the subject of oil company interest in the offshore basins both for a source of oil as well as a reservoir. In fact, petroleum can be found on fracture surfaces in exposures of the Monterey south of Limantour Beach. We will examine the Monterey at Kehoe Beach.

Santa Margarita Sandstone. The transgressive Santa Margarita Sandstone unconformably overlies the Monterey. The greenish lithic arkose is glauconitic at its base and grades upward into the overlying Santa Cruz Mudstone. The sandstone averages 5 to 20 meters thick. Except for outcrops exposed along the beach east of Drakes Bay, the sandstone is poorly exposed.

Santa Cruz Mudstone. The Santa Cruz Mudstone consists of siliceous mudstone and porcelanite. It thins rapidly northwestward from 1040 meters near Bolinas to where it pinches out north of the east end of Limantour Spit. It has been dated as Delmontian (Latest Miocene) from benthic forams. Because it pinches out before the exposure reaches the cliffs at Drakes Beach, we will not have the opportunity to examine it.

Purisima Formation. The Purisima Formation conformably overlies the Santa Cruz Mudstone. About 490 meters thick, it is best exposed in the cliffs at Drakes Beach. The rocks are locally diatomaceous, light olive gray siltstone with carbonate concretions and some sandstone. The top has been removed by erosion so the Purisima represents the top of the sedimentary section at Point Reyes. It has been dated as mostly Late Miocene and the topmost portion is considered Pliocene.

Tectonic History of Point Reyes

A good description of the tectonic history of Point Reyes can be found in Clark and others (1984), which has been included in the appendix of this guidebook. A short description of the origin of Point Reyes and the Salinian Block, however, would be useful here.

The Salinian block, of which Point Reyes is the northern part, is about 40 to 70 km wide and more than 500 km long. The block is sandwiched between two major strike-slip faults, the San Andreas and the Sur-Nacimiento faults. The block has moved northwestward relative to North America along the San Andreas fault. The anomalous feature about the block is that it appears to be a piece of continental plutonic arc flanked on both sides by Franciscan-type rocks.

The San Andreas fault, which bounds the block on the northeast, is better exposed than the faults that bound the southwest side. Studies of offset along the San Andreas can help explain the block's origin. The San Andreas transform fault supposedly was born when the continent met the East Pacific rise spreading center 29 mybp during the Oligocene. Displacements along the San Andreas are well-documented for rocks dating as far back as the Eocene, showing 305 to 330 km of offset since the Early Miocene (ca. 23 mybp, Clark and others, 1984). When the post Eocene offset is restored, however, nearby pre-Eocene basement rocks on either side of the fault do not match. One has to add up to another 230 km of offset to line up the basement granites just north of Point Reyes with Sierran granites and the southern California batholith (Hill and Dibblee, 1953).

Suppe (1970) suggested movement along a proto-San Andreas to explain the missing offset. Another explanation was to take up the offset along faults within the Salinian block (Johnson and Normark, 1974). Work by Clark and others (1984) may support the latter theory. They showed at least 150 km offset on the San Gregorio fault over the last 11 to 12 m.y. (see Figure 8, in Clark and others, 1984). Offset along the same fault occurring before 12 mybp could help to explain the missing 230 km.

Some workers have proposed that the missing offset may be even greater. Ross (1978) felt that the granites of Salinia were not similar in character to the granites of the Sierra Nevada or the southern California batholith. Page (1982) suggested that the granites in the Salinian block may have come from thousands of kilometers to the south based on an examination of Ross' data, recent paleomagnetic data (eg. Champion, Grommé, and Howell, 1980) and studying the faults to the southeast of Salinia. Originating at the latitude of Central America or Mexico, the block may have been rafted northward on oceanic crust.

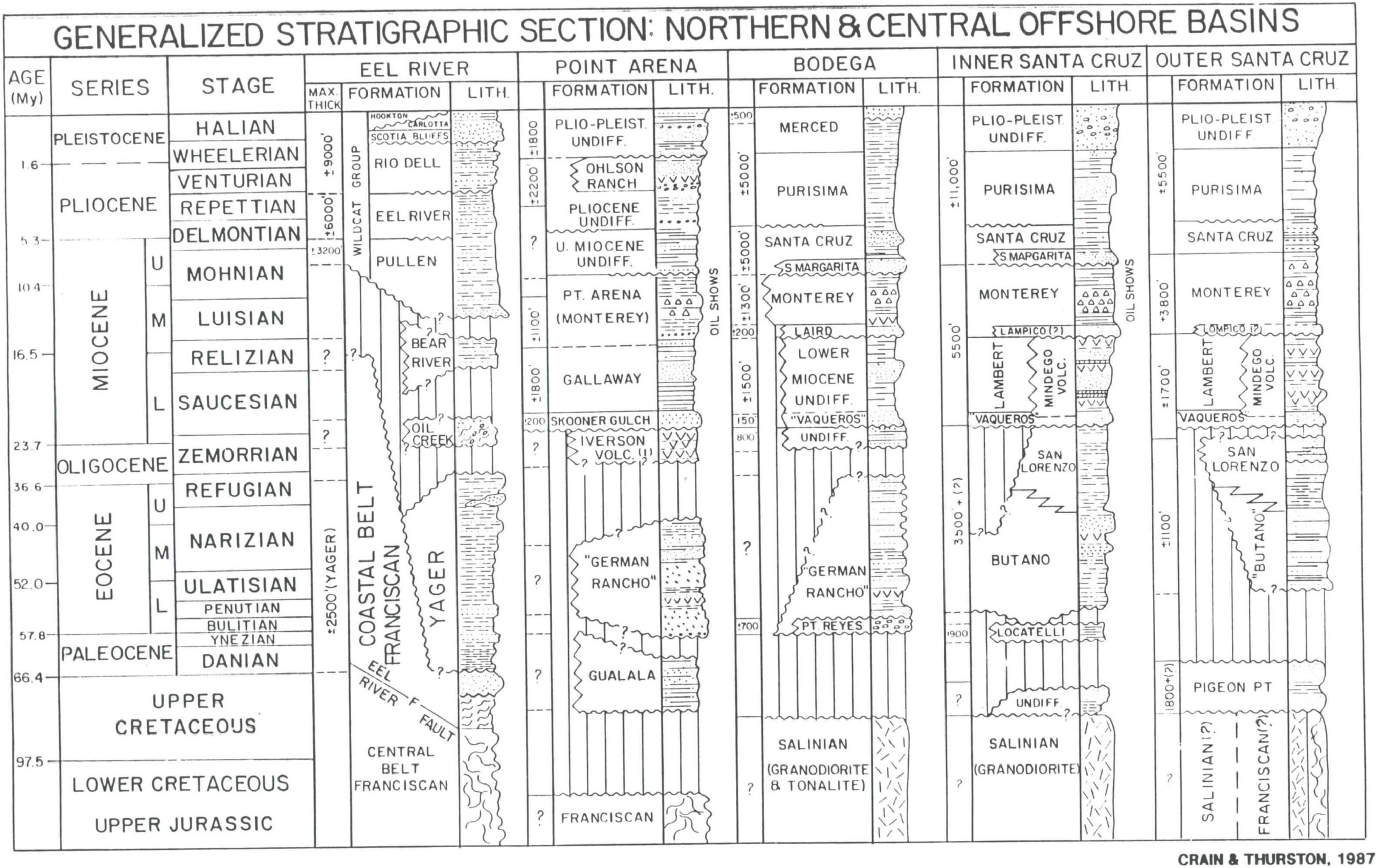


Figure 6. Generalized stratigraphic column for the coastal land and offshore basins in central and northern California (from Crain and Thurston, 1984).

OFFSHORE GEOLOGY AND PETROLEUM ASSESSMENT

by Rusty Gilbert

The Bodega Basin lies offshore from Point Reyes and extends as far north as the town of Gualala (see Figure 3). The eastern margin of the basin is defined by the San Andreas Fault. The southwestern margin of the basin is defined by the Farallon Ridge, an uplifted granitic block extending through the Farallon Islands and Cordell Bank. Both diorites and tonalites have been sampled from the Farallon Ridge (Chesterman, 1952; Hanna, 1952; Ross, 1984). Scattered outcrops on Point Reyes Peninsula record the only preserved stratigraphy for the southeastern portion of the basin. These outcrops include potential offshore reservoir targets such as siliceous shales of the Monterey Formation and pre-Monterey sandstones.

The Santa Cruz Basin is located south of Point Reyes and Bodega Basin (see Figure 3). This basin is bounded on the east by the San Gregorio fault. Coastal outcrops occur just west of the San Gregorio fault but will not be visited on this field trip. The Santa Cruz Basin can be subdivided into Inner (northeast) and Outer (southwest) basins by the Farallon Ridge and Pigeon Pt. High anticlinorium.

Previous Offshore Exploration Activity

California's first offshore leasing in federal waters occurred on May 14, 1963, when the P-1 Lease Sale was held for the central and northern California basins including Bodega and Santa Cruz basins. Following the lease sale, Shell Oil drilled ten exploratory wells in Bodega basin and two in Outer Santa Cruz basin. No other competitor drilling took place in these basins. The results of wells drilled on P-1 leases were made public on December 1, 1974 (Zieglar and Cassell, 1978).

Bodega basin drilling occurred from December 1963 to February 1967. Water depths ranged from 200 feet (61 m) to 440 feet (134 m). Normal mud weights were used and no significant drilling hazards were encountered (Zieglar and Cassell, 1978). Many of the wells tested major structures according to Hoskins and Griffiths (1971). A structural trend interpretation by McCulloch (1987), summarized in Figure 3, uses primarily high resolution and intermediate penetration single-channel seismic reflection surveys. The map shows that the majority of the wells were drilled along anticlinal axes.

Cretaceous granitic basement is present beneath Bodega Basin and affects the structural style (Hoskins and Griffiths, 1971). Both the P-039-1 and P-041-1 wells penetrated granitic rock at T.D. (Zieglar and Cassell, 1978). In many of the wells, potential reservoir sandstones, often containing oil shows, were encountered below the siliceous Monterey shales. The only drill-stem test conducted in Bodega basin was at the P-027-1 well over a sandstone interval in the lower part of the Miocene (Minerals Management Service, 1983). Only drilling mud and water were recovered. Siliceous and cherty shales of the Miocene

Monterey Formation also occur in the basin and are described as naturally fractured with tarry oil in the fractures. Younger claystone and shale overlie the Monterey Formation and may serve as a hydrocarbon seal.

Lease Sale Status

Over the last ten years several Federal OCS lease sales which included Bodega and Santa Cruz basins were rescheduled or cancelled. OCS Sale 119, which includes the Bodega and Santa Cruz basins, is currently scheduled for March 1991. The Area of Call for Nominations (see Figure 3) represents the largest possible area that could be offered for leasing. It includes blocks ranging from 3 to 45 miles offshore from Sonoma, Marin, San Francisco, San Mateo, Santa Cruz, and Monterey Counties. The Area of Call does not include sensitive areas near Point Reyes and the Farallon Islands or over Cordell Bank.

President Bush has assembled a special task force to advise him on energy and environmental needs prior to any final determination on leasing in northern and southern California affecting OCS sale areas 91 and 95. The task force is expected to give their recommendation by January 1, 1990, and their conclusions will undoubtedly also affect the status of OCS Sale 119 in central California.

HISTORY OF THE POINT REYES PENINSULA

by Art Fuller

The chief of a Coastal Miwok village stood on the cliff nearly 300 feet above the surf looking at a large floating object approaching the shore. His people had lived in this area for centuries following their migration from the far north. He had never seen a sailing ship nor white faces before. They were to change his life and the makeup of the region forever.

The year was 1579 and the place would become known as the Point Reyes Peninsula. The first Europeans ventured to the area on a weather beaten ship known as the Golden Hinde commanded by Francis Drake. Although there is controversy as to whether Drake first landed at Drakes Bay, his experiences during his five weeks in the area which he called Nova Albion are well documented in the log of his chaplain, Francis Fletcher. Drake claimed the "land of faire and goode baye" for his ruler, Queen Elizabeth I, and was later knighted for his effort.

Many shipwrecks took place in the vicinity of Point Reyes. One of the first was Sebastian Cermeno's galleon San Agustin which was destroyed and several of the crew drowned at Drakes Bay in 1595. Ironically the Portugese captain had been commissioned by the Spanish Government in Mexico to search for safe harbors. In January 1603, one of the survivors of Cermeno's voyage, Sebastian Vizcaino, arrived off the peninsula on Three Kings Day and named it La Punta de los Reyes, the Point of the Kings.

Point Reyes was part of the Spanish Colony, Alta California, but the Spanish never settled on the peninsula. Russian occupation of nearby Sonoma County began in 1812. During their stay Russian stone masons built several lime kilns on the peninsula. They used the lime to tan hides, manufacture brick and tile, and to make white wash which they applied to their wind mills, farm buildings, granaries, storehouses and cattleyards. After Mexico gained its independence from Spanish rule in 1821, land grants were established in California. In 1836, Point Reyes was granted to James Berry and an Irishman, who had been a colonel in the Mexican army, and Rafael Garcia. Berry illegally sold part of his land and hired Garcia as foreman of his cattle ranch while Garcia turned over part of his share of the grant to his brother-in-law leaving the ownership in a muddled state.

Following the American conquest of California in 1846, ownership of the peninsula was taken over by three lawyers from Vermont; the Shafter brothers and Charles Howard. The Shafters began leasing their land to dairy farmers in the 1850s and the area became famous for its butter and hogs which were regularly shipped to San Francisco. The Lighter Wharf built in the early 1850s in Bolinas served as a loading port for timber being moved to deeper water for transfer to ships taking it to San Francisco.

In 1865, a road was completed from Olema to San Rafael and later, in 1875, the North Pacific Coast Railroad put in a line from Sausalito through Point Reyes station to Tomales. James Shafter had invested and lost heavily in the railroad. To recoup some of his losses and pay off his creditors, Wells Fargo and Leland Stanford, he created the town of Inverness in 1889. Following James' death his daughter Julia sold 110 acres of Bear Valley to the Pacific Union Club in 1895 for $6,000. Pacific Union created a country club where San Francisco's elite and guests such as Teddy Roosevelt came to hunt deer, bear and mountain lion which were prolific on the peninsula.

As an aid for navigators, the Point Reyes Coast Guard Lighthouse was opened in 1870 on the cliff where the Miwok chief had stood nearly 300 years earlier. The peninsula had become known as the windiest and foggiest point on the West Coast by the schooner captains who carried timber, firewood, poultry and eggs to San Francisco.

The 1906 earthquake destroyed many buildings on the peninsula. Knowledge of the destruction spread and potential investors changed their minds about developing Point Reyes. During prohibition, bootlegging operations flourished on the peninsula. Liquor was also transferred from ships from Canada to trucks which carried the cargo to markets inland.

In 1935 the National Park Services recommended purchase of 53,000 acres at Point Reyes for $2.4 million. Since the country was recovering from the depression, the purchase was not made. A few county parks, however, were created at Drakes Beach, McClures Beach and Tomales Bay. These were established due to strong conservationist pressure after a Los Angeles developer announced plans to subdivide many acres and construct deluxe villas, golf course and a polo field.

Despite the fact that loggers were stripping the Point Reyes ridges it took until 1962 for conservationists and California Senator Clair Engle and Congressman Clem Miller to convince President John Kennedy to sign the Point Reyes National Seashore Bill which authorized expenditures of $13.2 million for the original acreage recommended in 1935. Final costs of the park amounted to $56 million with acquisitions being completed in 1970. A Citizen's Advisory Commission was established in 1972 to oversee the development of Point Reyes. This group has been instrumental in seeing to it that the area is left unchanged and that 32,000 acres were designated as wilderness and 18,000 acres were zoned for long-term grazing.

Although Point Reyes is still a beautiful place, it has changed considerably through the years. The Miwoks of Drake's era certainly would miss the heavily forested slopes and abundant wildlife.

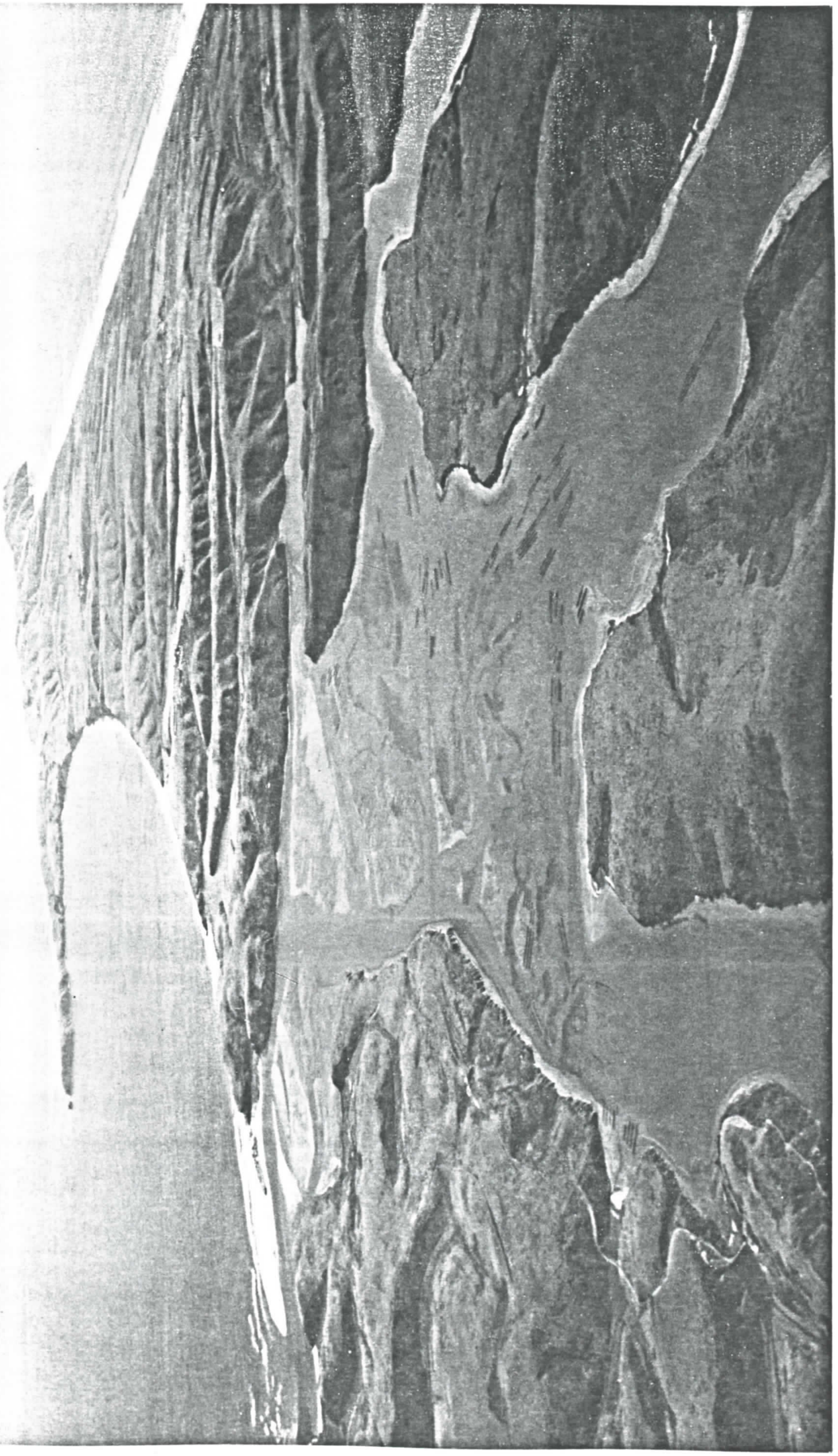


Figure 7. Aerial photograph of Drakes Estero and Point Reyes looking west.

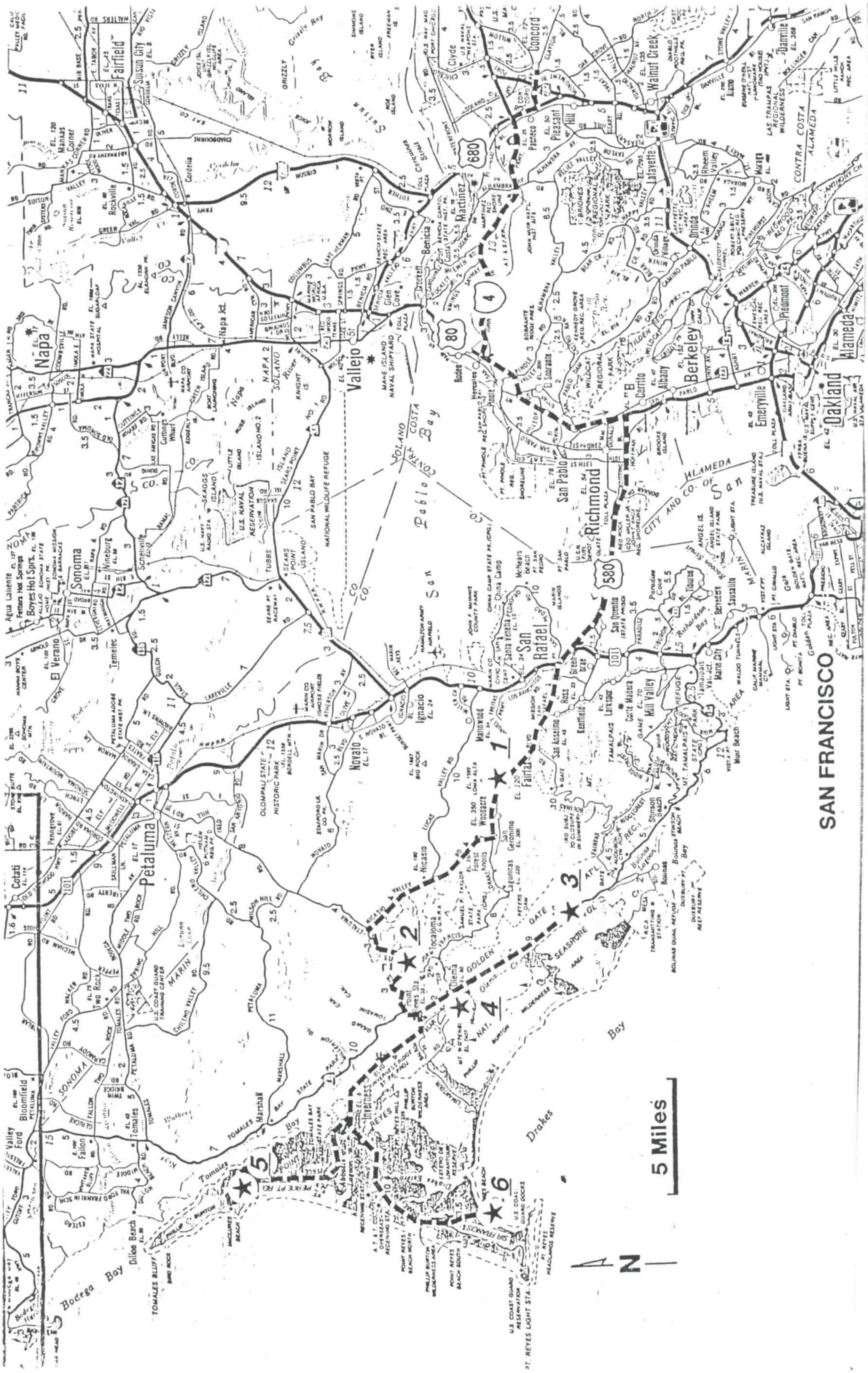


Figure 8. Route map of the Point Reyes field trip. Courtesy of American Automobile Association of California.

INTRODUCTION

The trip begins in the Franciscan assemblage in northern Marin County. The Franciscan dominates the geology of coastal northern California east of Point Reyes and documents a very important episode in the geologic history of California, one of Mesozoic and Early Tertiary subduction. We will examine the Franciscan in two stops, the first an examination of graywacke and melange, and the second at a beautiful exposure of pillow basalts.

The Franciscan is separated from Point Reyes Peninsula by the San Andreas fault. The San Andreas marks the tectonic boundary between two large tectonic plates, the North American continental plate and the Pacific oceanic plate. The fault has had a major effect on the geology in California and represents one of the most interesting geological features of the Point Reyes area. We'll examine the fault in two stops, the second aided by the National Park Service's displays at the Bear Valley Visitor Center where we plan to eat lunch.

After lunch we head for the beach to examine the geology of Point Reyes Peninsula in two stops. At both stops the rocks are exposed in sea cliffs, offering a spectacular cross-section of almost the entire stratigraphic section present at Point Reyes.

BEGIN ROAD LOG

Leave from the Chevron USA Concord office, 2001 Diamond Blvd, Concord at 8:00 AM.

Head north on I-680, exiting at the junction with California Route 4 West toward Martinez. At the intersection with I-80, head south toward Oakland. Exit I-80 at Cutting Blvd in Richmond and drive west toward the San Rafael Bridge.

The roadcuts visible to the left and right on the approach to the San Rafael Bridge expose sandstones and graywackes of the Franciscan complex. Blake and others (1984) include these units in their "Novato Quarry terrane," which extends northwest from the Richmond area to Bodega Bay. These rocks are considered to be Late Cretaceous (Campanian) in age (Bailey and others, 1964), and are inferred to have been deposited at the fringe of a submarine suprafan. The Novato Quarry terrane of Blake and others represents one of the most coherent masses in the Franciscan Complex, and also one of the youngest.

The red island visible on the left close to the bridge just past the toll plaza is Red Rock, which was for sale a number of years ago. It is composed of Franciscan chert. The tiny island was once known as Golden Rock because pirates were supposed to have buried treasure there.

The prominent peak ahead at about 11:30 o'clock is Mount Tamalpais. It is underlain by an erosion resistant, hydrothermally altered sandstone in the Franciscan melange. Mount Tamalpais was once known as Table Mountain, coined by Beechey in 1826, because it has a flat top when viewed from the ocean off Point Reyes. The origin of the name Tamalpais is uncertain but probably came from the local Indians.

Driving across the bridge is a great time to examine the bay and picture when sea level was 100 feet lower than today. Try to imagine the great Pleistocene Sacramento River flowing in a deep canyon past Angel Island and out the Golden Gate.

PLEISTOCENE HISTORY OF SAN FRANCISCO BAY

by Norma Biggar

The San Rafael Bridge is a good place to look southward toward the Raccoon Straits between Angel Island and Tiburon and the Golden Gate. You are looking along the former drainage channels of the Sacramento River during the Pleistocene, when sea level was about 300 feet lower than it is today. Subbottom profiling of the bedrock surface beneath the bay (Carlson and McCulluch, 1970; Carlson and others, 1970) has revealed a bedrock gorge up to 200 feet deep below present sea level underneath Raccoon Strait. Up to 150 feet of sediment has accumulated in this channel, which still serves as one of the primary paths of water movement between the ocean and the Sacramento River. The channel through Raccoon Strait is linked with the 350 foot deep trough beneath the Golden Gate and is the best developed of the bedrock channels. Other channels were cut between Angel and Alcatraz Islands, between Alcatraz Island and San Francisco, and on the east side of Angel Island, where a channel is oriented north-south. The bedrock surface at the mouth of Richardson Bay, which separates the Marin and Tiburon peninsulas, appears to be about 150 feet below present sea level.

The San Francisco Bay and the channel through the Golden Gate are geologically young features. As recently as 1 million years ago an estuary connected southern San Francisco Bay with the Pacific Ocean via a shallow marine embayment in which sediments of the Merced Formation were deposited south of San Francisco. Fresh water drained to this estuary from the Central Valley, as evidenced by the presence of Great Valley detritus in part of the Merced Formation (Hall, 1966, in Atwater and others, 1977). These sediments were later deformed and uplifted. Tectonic subsidence in the area over the last 1.5 m.y. has amounted to at least 100 meters in places. Some Holocene salt marsh deposits have subsided about 5 meters in the last 6,000 years (Atwater and others, 1977).

Sediments studied in the southern Bay by Atwater and others (1977) record estuaries that formed during high stands of sea level in Sangamon and post-Wisconsin time (100,000 and 10,000 years ago, respectively). They found that the last major sea level rise began 10,000 to 11,000 years ago and continued until 8000 years ago. The ocean entered the Golden Gate and the sea spread across land areas as rapidly as 30 meters/year. Since that time, shore line and sea level changes have been much more gradual.

After crossing the bridge, exit the freeway at the US 101 south offramp, and stay on Sir Francis Drake Blvd.

After exiting the freeway, the road climbs a hill just north of San Quentin Prison formed of Franciscan melange. The hills to the right are dotted with quarries, some of which have been converted into shooting ranges. The road descends down to Larkspur Landing.

Approaching Larkspur Landing you pass a large brick smokestack which is surrounded by a new office complex. The stack is over the old brick kiln of the Remillard Brick Company. The plant was built in 1891, and once had the capacity of 12 million bricks per year (Bowen, 1951). "Weathered clay shale" (likely melange material) of the Franciscan was the primary raw material used. Melange material quarried nearby was also hauled to the Sacramento River delta to build dikes.

The Larkspur Landing shopping and condominium complex just beyond the stack was built on the site of the former quarries of the Hutchinson Company. Green-gray, hard (jadetized?) Franciscan sandstone supports the near vertical cliff faces of the quarry, whereas melange underlies the rubbly, slide-prone slopes. The tan condos closest to the cliff are protected from rock falls and slides by a moat about 8 feet deep.

The Larkspur Ferry terminal is on your left while driving through Larkspur. The high-speed ferries were to provide an alternate commute route for Marin County residents, but the large wakes created by the boats caused excessive erosion of the bay shores. The boats now travel at considerably less speed than they are capable.

The ferry terminal is at the mouth of Corte Madera Creek, and Sir Francis Drake Blvd. follows the course of the creek as far as San Anselmo. The creek's banks have been extensively developed and the creek is now restrained to a narrow channel. Consequently, whenever a big Pacific storm dumps several inches of rain in a short time, Sir Francis Drake Blvd. floods.

After passing under U.S. 101, you should notice a hill behind the Bon Air shopping center on the left. It is a large block of greenstone in the Franciscan melange.

Continue driving through the Marin County settlements of Kentfield, Ross, San Anselmo, and Fairfax on Sir Francis Drake Blvd. Incidently, the town of Ross contains some of the most expensive real estate in the country. It was named for James Ross, who acquired Rancho Punta de Quintin in 1859. This drive takes you through a particularly well broken up part of Franciscan melange.

At the entrance to Fairfax's city limits, note mileage.

Just 3.0 miles past the Fairfax city limits, pull off the road on the wide shoulder near the top of the hill for Stop 1.

STOP 1

FRANCISCAN ASSEMBLAGE AND LANDSLIDE

No field trip to an area in northern California is complete without a visit to the Franciscan assemblage. Almost all of Marin County is composed of Franciscan melange, a mixture of mudstone, graywacke, greenstone, and other various rock types. Our first stop provides us with a good exposure of Central Melange Belt graywacke, Franciscan melange, and the ever-present landform which develops on outcrops of melange, a landslide or earth flow.

Walking uphill from the parking area, you should notice some large boulders on the side of the road which were removed from the earth flow of melange. These boulders are made of representative rock types of the Franciscan: graywacke, serpentinite, and pervasively sheared mudstone. Farther up the road, the mud oozing down onto the pavement is formed mainly in the melange mudstone matrix with some more coherent blocks of sandstone and other lithologies mixed in. The road cut farther up the hill is cut through a large outcrop of bedded turbidite sandstones which exhibit graded bedding. If you were to follow the bedding however, you would find that this outcrop is completely surrounded by mudstone (see Figure 9). The outcrop is just an even larger coherent block or "knocker" in the Franciscan melange. Read the sections below on the Franciscan and the landslide for a better understanding of this exposure.

FRANCISCAN ASSEMBLAGE

The Franciscan assemblage has been an object of intense study since it was first described by Blake (1858). Commonly called the Franciscan Complex, its structure and stratigraphic relationships are most enigmatic and not at all like most mappable units. Today, most people agree that the Franciscan originated in a wedge zone formed above a subducting oceanic plate (see Figure 1). The origin of the rocks within the Franciscan, however, is still a subject of controversy.

Descriptive Geology

The Franciscan assemblage is a belt of highly deformed and variably metamorphosed graywacke, mudstone, volcanics, and chert occupying the coast of California from Santa Catalina Island to Oregon. Dated as coeval with the Great Valley Sequence just to the east, the Franciscan differs from the Great Valley in lithology, structure, and possibly provenance.

Figure 9. Geologic map of Stop 1. Map symbols: KJfs-Franciscan melange, KJfss-Franciscan sandstone, KJfg-Franciscan greenstone, KJfm-Franciscan high-grade metamorphics, sp-serpentinite, ch-chert, gs-greenstone, m-metamorphic rock, mch-metachert (from Blake and others, 1974).

The Franciscan has been divided into three major units which trend roughly parallel with the coast (see Figure 10). From west to east they are the Coastal Belt, the Central Melange Belt, and the Metamorphic or Yolla Bolly Belt (Blake and Jones, 1981).

Coastal Belt. The Coastal Belt is the westernmost of the three units in the Franciscan. Dated as Late Cretaceous to Miocene, the Coastal Belt is also the youngest and least metamorphosed. The unit consists mainly of bedded graywacke and mudstone which is highly faulted, a structure known as a broken formation. The sandstones tend to be more arkosic with less volcanic and chert lithic clasts than the other belts. The Coastal Belt appears to have been thrust under the Central Belt along a major shear zone.

Central Belt. The Central Belt is primarily melange, with large blocks of graywacke and metagraywacke, smaller blocks of greenstone, chert, and serpentine, with lesser limestone, amphibolite, blueschist, and eclogite knockers in a sheared mudstone matrix. Blake and others (1984) have divided the Central Belt into 9 different tectonostratigraphic terranes. Fossils recovered from the matrix have shown this zone to be Late Jurassic to Early Cretaceous in age, but the blocks range as young as Late Cretaceous. The average metamorphism of the matrix is slightly higher-grade than the Coastal Belt, but high-grade blueschist blocks are common along the contact with the Coastal Belt. One of the puzzles of the Franciscan is how high-grade metamorphic blocks can be immersed in a matrix of relatively low-grade mudstone matrix. Interestingly, one of the limestone blocks found in this unit was determined to have been deposited at a latitude 17° south of the equator (Alvarez and others, 1980). It is believed to have been deposited originally on top of a seamount which was scraped off in the subduction zone. We will examine a pillow basalt in the Central Belt at our second stop which also has apparently travelled a long way, in fact, 2000 km according to Page (1982).

Metamorphic Belt. The Metamorphic or Yolla Bolly Belt crops out discontinuously to the east of the Central Belt. The unit is the most metamorphosed of the three belts, although higher-grade eclogite knockers occur in the Central Belt. The Yolla Bolly Belt contains metagraywacke, quartzofeldspathic schist, metachert, metagreenstone, mudstone, and basaltic tuff. The rocks have been dated with fossils as Early Cretaceous. The metamorphism has been dated radiometrically as 115-120 m.y. or Early Cretaceous (Blake and Jones, 1981). The unit is bounded on the east by the so-called Coast Range thrust, a sharp, often sheared contact with the unmetamorphosed Great Valley Sequence which appears to structurally overlie the Franciscan.

Great Valley Sequence. The Great Valley Sequence lies just to the east of the Franciscan but is relatively undeformed and unmetamorphosed. Dated as Late Jurassic to Latest Cretaceous, the sediments apparently formed at the same time as the Franciscan, having been deposited on a piece of oceanic crust known as the Coast Range ophiolite. The Great Valley Sequence consists of well-bedded mudstone,

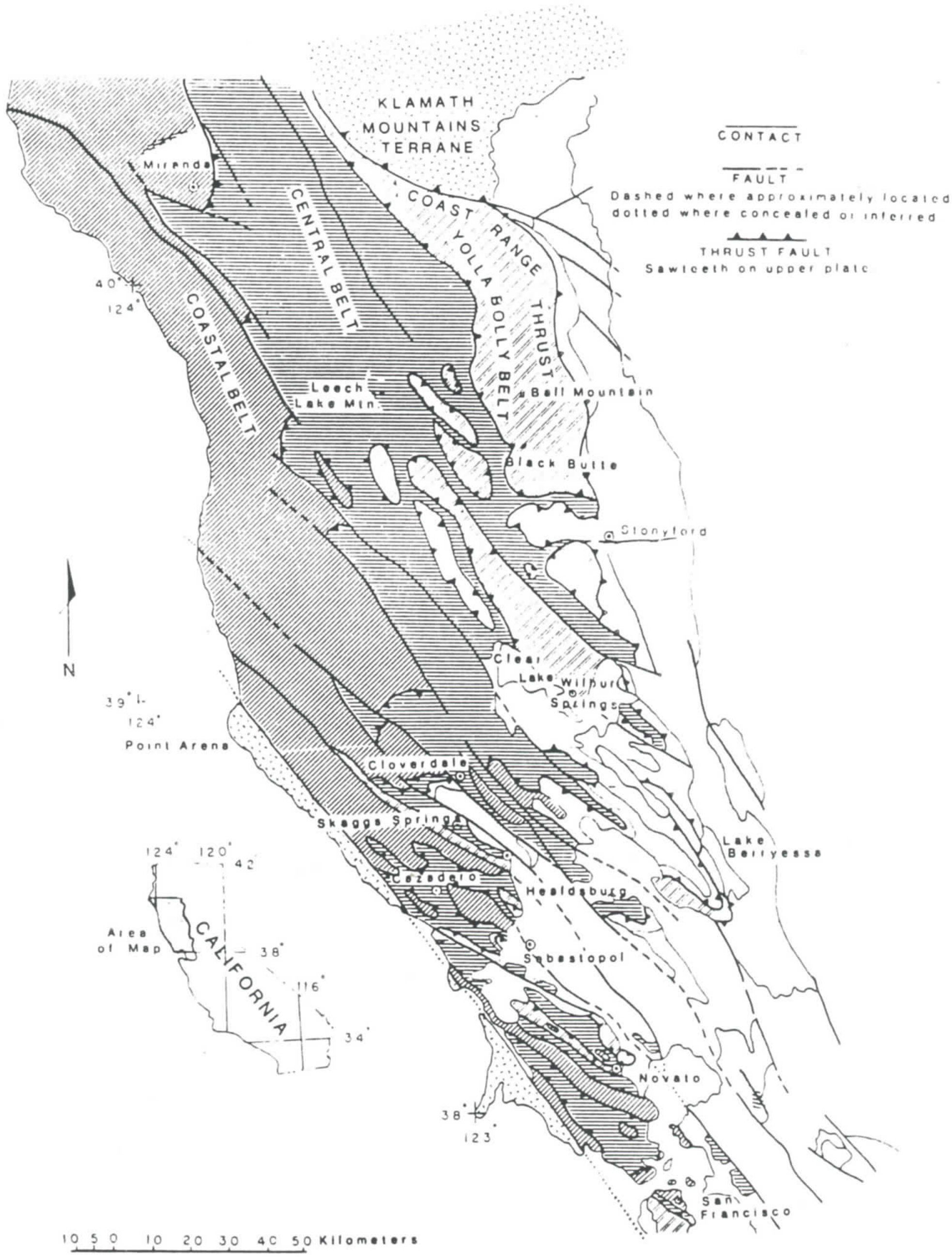


Figure 10. Lithotectonic belts of the Franciscan assemblage, northern California Coast Ranges (from Blake and Jones, 1981).

siltstone, sandstone, and conglomerate was deposited by turbidity currents in a fore-arc basin setting west of the North American continent. The stratigraphic sequence records the stripping off of the volcanic cover of the Sierra Nevada and Klamath granite batholiths (Dickinson, 1982).

Interpretive Geology

The Franciscan is believed to have formed within an accretionary wedge above the down-going plate in a subduction zone. How the melange formed and where the Franciscan rocks originated is still controversial. Some workers believe that the melange formed mainly by olistostromes or giant submarine slumps while others propose that it is mostly by tectonic mixing. Some believe that the blocks within the melange were sourced from the same areas as the Great Valley Sequence, and others think they originated thousands of kilometers to the south.

Melange Formation. Franciscan melange is believed to form above the subducting oceanic plate. Much of the marine sediment and other material riding on the oceanic plate is scraped off by the continent in the subduction zone (see Figure 11). In a continual process of tectonic mixing, the material is eventually underridden by more material and a wedge is eventually formed (Page, 1981). As more material is wedged underneath the submarine face of the wedge oversteepens and large slumps or olistostromes occur, transporting material back into the trench to be subducted again. This model can explain the apparent juxtaposition of rocks of rather different metamorphic histories.

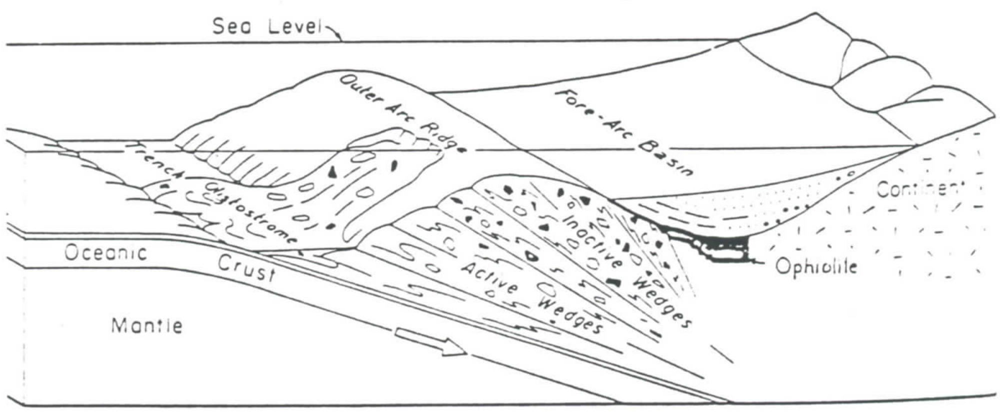


Figure 11. Diagram of possible mode of origin of Franciscan melanges, showing postulated interplay between subduction and olistrome flows. Blocks shown in black are distinctive older materials, e.g., serpentinite, blueschist, oceanic basalt, Upper Jurassic chert. Coherent sedimentary units omitted for simplicity (from Page, 1981).

Franciscan Provenance. One of the great controversies of northern California geology is the origin of Franciscan rocks. Franciscan sediment is coeval with the Great Valley Sequence and many workers believe that the Franciscan mudstones, sandstones, and conglomerates had the same source as the Great Valley. Dickinson (1982) describes a sedimentary petrography study which shows a correlation between the rocks of both formations, implying a common source. Using similar data, Blake and Jones (1981) argue that the sediment is too dissimilar and must have originated many miles south of the Great Valley Sequence. Furthermore, they note that the Franciscan is commonly coarser-grained than the Great Valley Sequence sediments. Hence, it would have been difficult to deposit coarse sediments like those in the Franciscan outboard of the forearc basin where the Great Valley was being deposited. Dickinson (1982) argues that submarine canyons could easily have transported such sediment beyond the basin.

Blake and Jones (1981) use their hypothesis to support the accretion of tectonostratigraphic terranes to North America from great distances, proposing that much of California and even western North America originated thousands of kilometers to the southwest. Dickinson (1982) prefers a much simpler model of a collapsed subduction zone whose components were simply juxtaposed when subduction ceased.

The controversy does not end here. However, this discussion does. After visiting the outcrop, form your own opinion. Perhaps with further work some of the puzzles will be solved.

LANDSLIDE AT TOP OF WHITES HILL

by Michael Carey

A cut slope on the right (north) side of the road just uphill from our parking area exposes a large active landslide. A well-developed headscarp is visible from the road, and another lies further upslope, slightly to the left. The slide is approximately 300 feet wide at the road and 1000 feet long. This active slide is within a mapped large ancient landslide deposit (Rice and others, 1976) which mantles most of the slopes in the region. The entire ridge is underlain by highly sheared and unstable rocks of Franciscan melange.

The toe of the active landslide has been undercut by road construction, and debris flows spill onto the pavement during heavy rainstorms. This has probably been happening ever since the road was built in the 1940s.

"Permanent" repair of this landslide probably would require removal of thousands of cubic yards of soil to construct an adequate buttress. Instead, the county has been removing the debris from the road when the slide moves. Horizontal drains have occasionally been installed in the slope in an attempt to drain the slide and slow its movement. As the broken and useless hydroaugers visible in the landslide show, these attempts are not always successful.

Hydroaugers. Hydroaugers are drilled horizontal holes usually used to remove excess water from unstable hillsides and landslides. They are usually drilled with a six-inch diameter rotary-wash rig. The holes can be drilled at variable angles, depending upon the situation.

When the hole is completed, a two-inch diameter perforated PVC pipe is inserted into the hollow drill pipe. The drill pipe is then carefully removed, leaving the perforated pipe in place. The last few sections of plastic pipe commonly are not perforated and can be connected together and drained as a unit onto a suitable nonerosive surface.

For further reading see the section entitled "Earth Flows in Inverness and the Rest of the Bay Area" on page 35.

ROAD LOG

Continue west on Sir Francis Drake Blvd. We pass rapidly out of the sandstone block as the road starts going downhill. Topography in the Franciscan is dominantly controlled by lithology, the more intact blocks of sandstone, greenstone, and metamorphics form the hills and ridges.

Just past the San Geronimo golf course, turn right on Nicasio Valley Road. The road here is climbing the southeast nose of a ridge held up by a large block of sheared metamorphic rock. The roadcuts expose sheared mudstone melange matrix and knockers of sandstone and crystalline rock.

Further on you enter a grove of coast redwoods (sequoia sempervirens). This lush forest is growing on the north side of the earlier mentioned block of sheared metamorphic rock. Part of this block is composed of high-grade schist.

As the road leaves the grove of redwoods, you come upon the intersection with Lucas Valley Road. Continue straight, following the road as it curves to the left.

About 0.5 miles past the intersection with Lucas Valley Rd. you enter the town of Nicasio. Be sure to follow the dogleg in the road to the left in town. The post office in Nicasio was established in 1870.

Just past town look to the right at about 3:00 o'clock. On the north side of Halleck Creek is a reddish chert block which appears to have been quarried, probably for road bed material. Most of the blocks you see sticking out of the melange here are chert. General Henry W. Halleck was Lincoln's General-in-Chief during the Civil War. He bought 30,000 acres here in 1851 for hunting and fishing.

About 2 miles past town, Nicasio Reservoir comes into view on the left. The rolling hills on both sides of the road are dotted with "knockers" of greenstone, serpentine, and chert of the Central Melange Belt. The large hill ahead at about 12:30 o'clock is Hicks Mountain, a large block of sandstone. The mountain is named after "Uncle Billy" Hicks who was an absentee landlord in this area. Hicks died in 1884 at his home in Hicksville, Sacramento County. Hicksville died shortly after him.

About 3.5 miles past Nicasio is the "T" intersection with Point Reyes Petaluma Road. <u>Note mileage</u>. <u>Turn left on Point Reyes Petaluma Road</u>. The rocks here are graywackes interbedded with shale.

After turning left note the large hill ahead or off to the left. Named Black Mountain, it is a large coherent block of greenstone pillow basalt which is our next stop. The mountain was named after James Black, who once owned it. Black was one of the first justices in the county.

Where the cliff begins on the right side of the road, <u>2.6 miles past the intersection</u>, <u>pull off the road to the right and park for Stop 2</u>.

BE CAREFUL as you exit the bus on this stop! The shoulder is narrow and cars drive by very fast.

STOP 2

NICASIO DAM PILLOW BASALTS

Visible at this stop is one of the best exposures of pillow basalts in the Franciscan assemblage. The road is narrow, however, and can be dangerous for large groups of geologists, so please be careful.

This part of the Franciscan is in the Central Melange Belt and constitutes a sequence of graywacke, serpentine, chert, and spilite (basalt with albite). The road cut exposes a mass of spilitic pillow lavas which apparently dips eastward at about 45° (see Figure 12). Individual pillows range in size from 6 inches to 6 feet in length. This outcrop is the northernmost of three basalt bodies which trend northwest from the northern flank of Mt. Tamalpais, about 25 km from this location (see Figure 4). The northwest trend is parallel to most of the bedding in the sandstone (Gluskoter, 1969). The lower, western contact with the sandstone is a shear zone where it is exposed, up to 30 meters wide (Wright, 1984). The upper contact with overlying sandstone appears to be conformable, but local shear zones are evident. Wright (1984) and Blake and others (1984) interpreted the basalt and the overlying sandstone and serpentine to be a single "terrane," calling it the Nicasio Reservoir terrane.

Pillow Structures. Pillow structures in basalt are indicative of lava which flowed underwater. The pillows form when the congealed cool crust of an active lava flow breaks and the molten lava spills out in a pillow-shaped blob. The cooling effect of the water causes a crust to harden on the outside of the pillow, and the flow stops momentarily. When the pressure builds up again, the crust breaks at one spot and another pillow spills out onto the ones below, resulting in a large pile of pillows such as you see at this stop. The outer rim of the pillows tend to be more vesicular than the center. The minerals in the rock are easily altered and chlorite is commonly formed. For that reason these rocks are often called greenstones.

Geopetal structures (up indicators) often can be found in pillow basalt outcrops. The top of the pillows are usually round whereas the base of the pillows are irregular, conforming to the pillows underneath. Chert can occur between pillows, suggesting a period of sediment deposition between active lava flows. The silica in the chert may be derived from the lava itself.

A common interpretation of pillow basalts in the Franciscan is that they originated as lava flows on the ocean floor. They may have occurred as localized eruptions on the open ocean floor, near an underwater volcano, or near a spreading center.

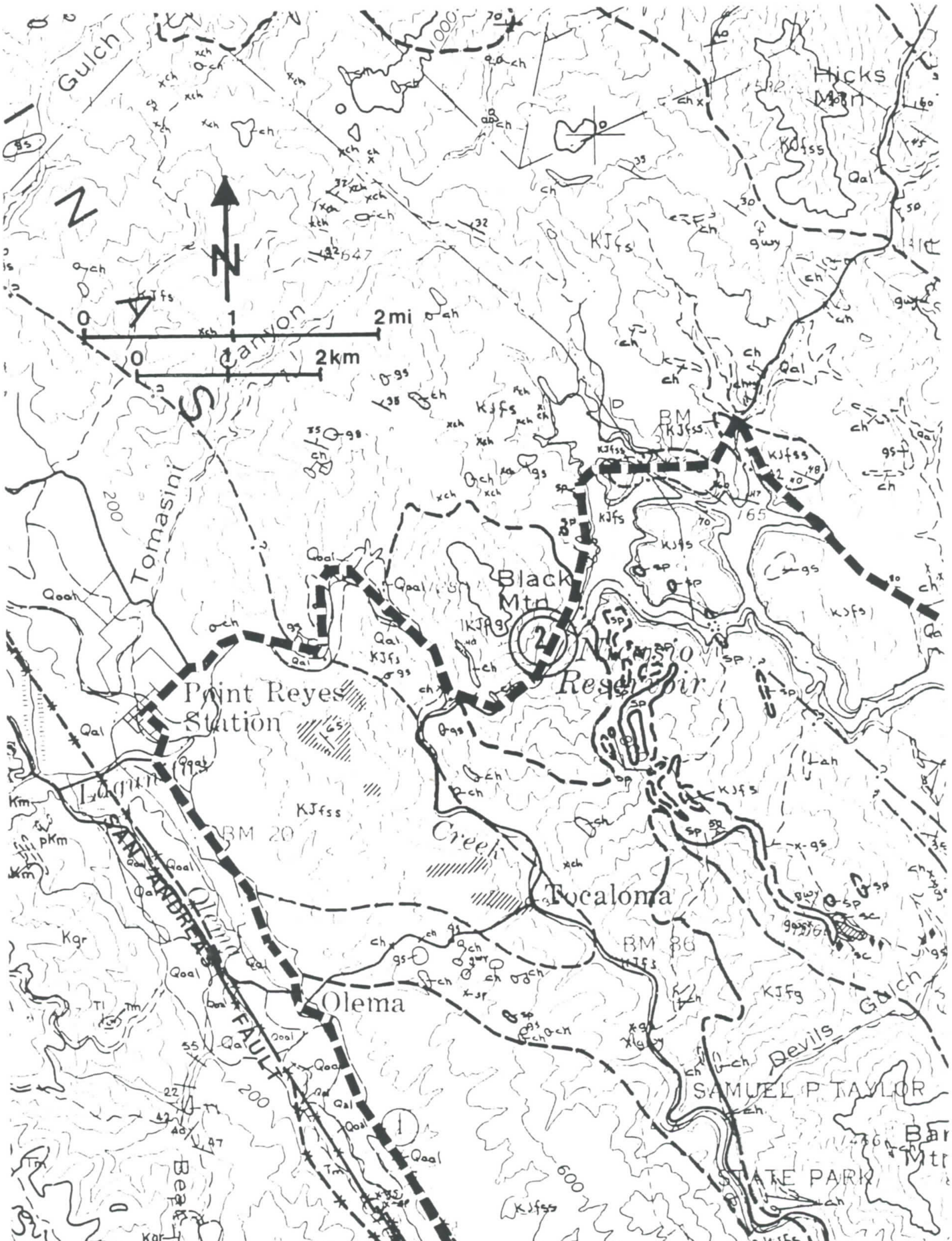


Figure 12. Geologic Map of Nicasio Dam area. Map symbols: KJfs-Franciscan melange, KJfss-Franciscan sandstone, KJfg-Franciscan greenstone, KJfm-Franciscan high-grade metamorphics, sp-serpentinite, ch-chert, gwy-graywacke, gs-greenstone, m-metamorphic rock, mch-metachert (from Blake and others, 1974).

Continue west down the Point Reyes-Petaluma Road. After a short drive, turn right at the stop sign toward Point Reyes Station. After another 3.5 miles, turn left onto Highway 1 toward Stinson Beach and Point Reyes National Seashore. Follow Highway 1 through Point Reyes Station, heading south toward Olema.

Just past Point Reyes Station the Highway 1 enters the fault zone of the San Andreas fault. A prominent pressure ridge is visible on the right. Other fault features are visible.

The next town is Olema, named after the Hookooeko Indian village which once occupied this site. Note mileage at the stop sign.

0.2 Road to Vedanta Retreat on your right. On this property renewed development of a number of previously formed fault-associated land forms was observed after the 1906 earthquake. This supported G. K. Gilbert's contention that the relief of previously developed fault-associated land forms was increased by the 1906 faulting.

1.0 The East Boundary Fault of the San Andreas Fault zone lies in the alluviated valley on your right. Up ahead, the fault is marked by scarps, linear valleys and sag ponds.

1.6 Highway 1 passes through a saddle developed on the East Boundary Fault just after the Truttman dairy ranch. Outcrops on the left are sheared Franciscan on the east side of the fault, ie., North American Plate. The East Boundary Fault lies 10-15 meters west of the road.

1.7 Linear valley and ridge on the right.

2.0 Sag pond on the left.

2.8 The East Boundary Fault lies beneath the green water tank on the left. A road cut along the east (left) side of Highway 1 exposes light colored laucustrine silts and clays of the Pleistocene Olema Creek Formation. These sediments were deposited in a fresh water lake that occupied part of the San Andreas Fault zone.

3.1 Alluviated valley along Olema Creek on the right. The 1906 trace is in the trees to the right about 400 meters from the road.

3.4 The trace of the East Boundary Fault lies at the base of the ridge on the left.

3.6 Cross Olema Creek. The Five Brooks Trailhead is to the right.

3.7 The East Boundary Fault passes between the house and barn on your left.

4.2 Highway 1 crosses a saddle. The trace of the 1906 rupture is immediately right of the road and is marked by a sag pond and a linear valley.

4.5 Highly sheared Franciscan serpentinite on the left.

4.9 The East boundary fault crosses the hillside to the left.

5.1 Olema Creek flows northward in the gully to the right. In this area Pine Gulch and Olema Creeks flow parallel to each other but in opposite directions separated by a medial ridge. This is an excellent example of fault-disrupted drainage.

5.4 East boundary fault trace runs through the yard of the white house to the left.

6.0 <u>Pull over and park on the turnout on the right for Stop 3.</u> These are private residences, so permission is needed to visit this stop. Exposures of Pleistocene stream terrace conglomerate opposite government housing driveway. East boundary fault is marked by the bench in the ridges to the left.

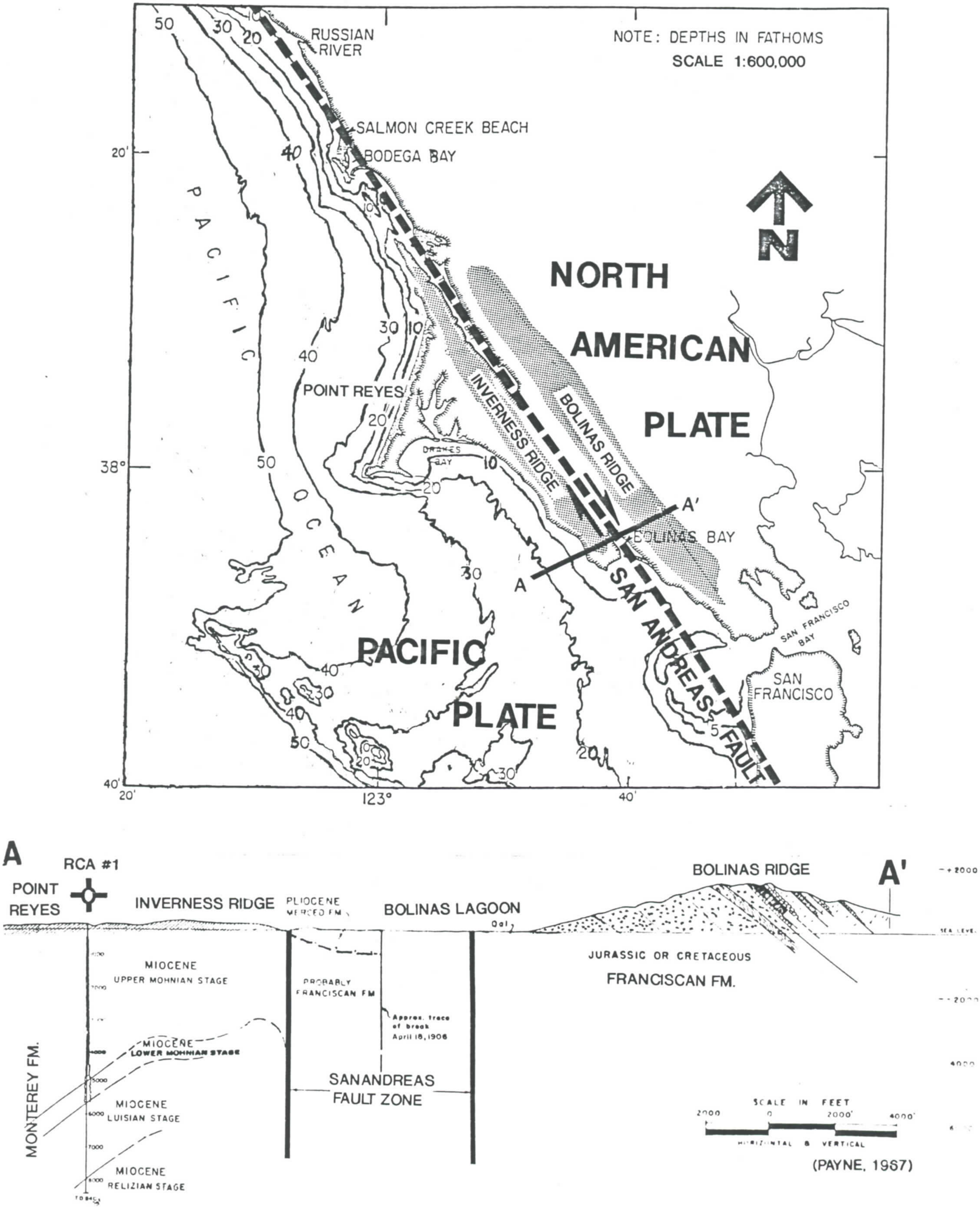


Figure 13. Tectonic map and cross section of San Andreas Fault Zone.

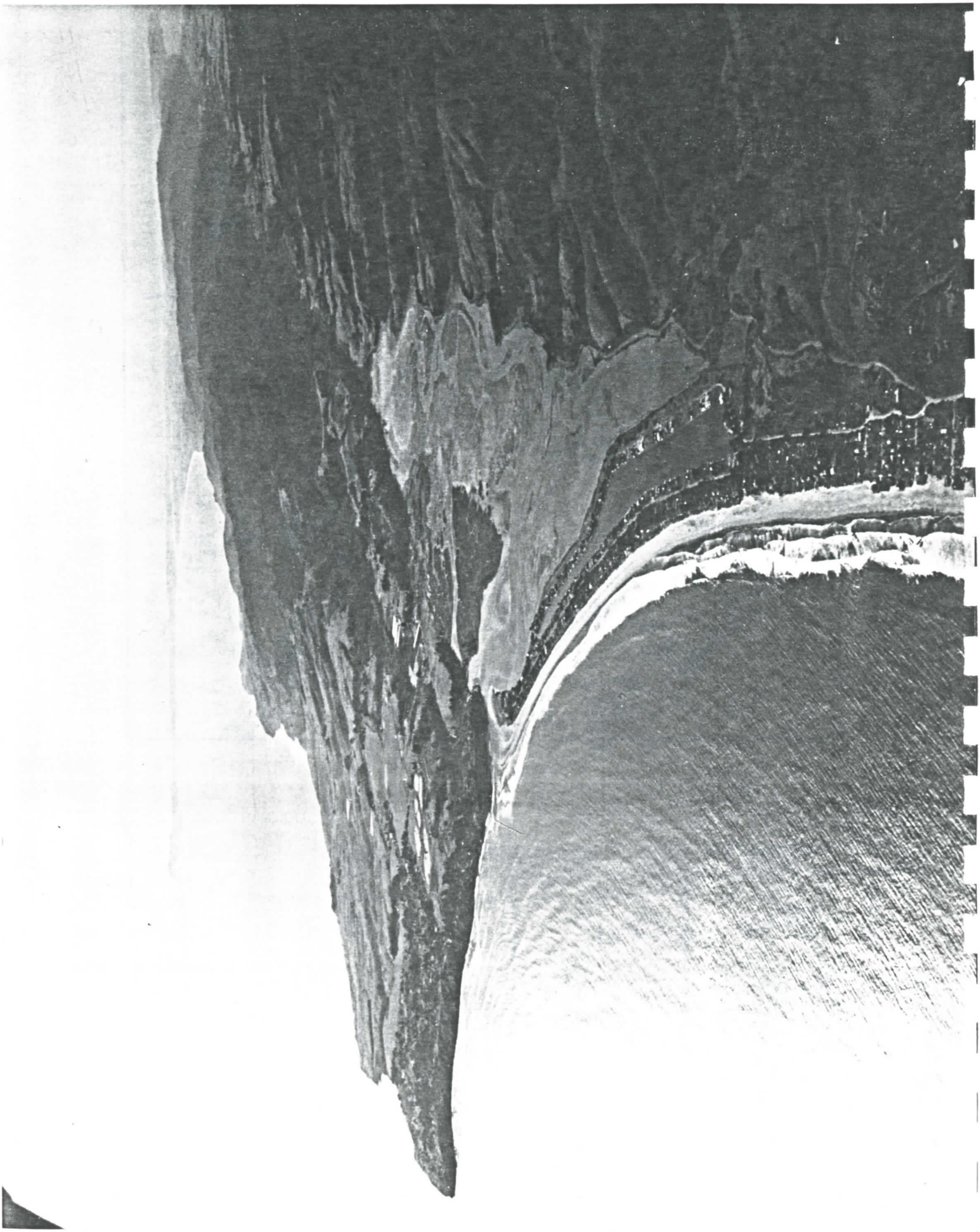
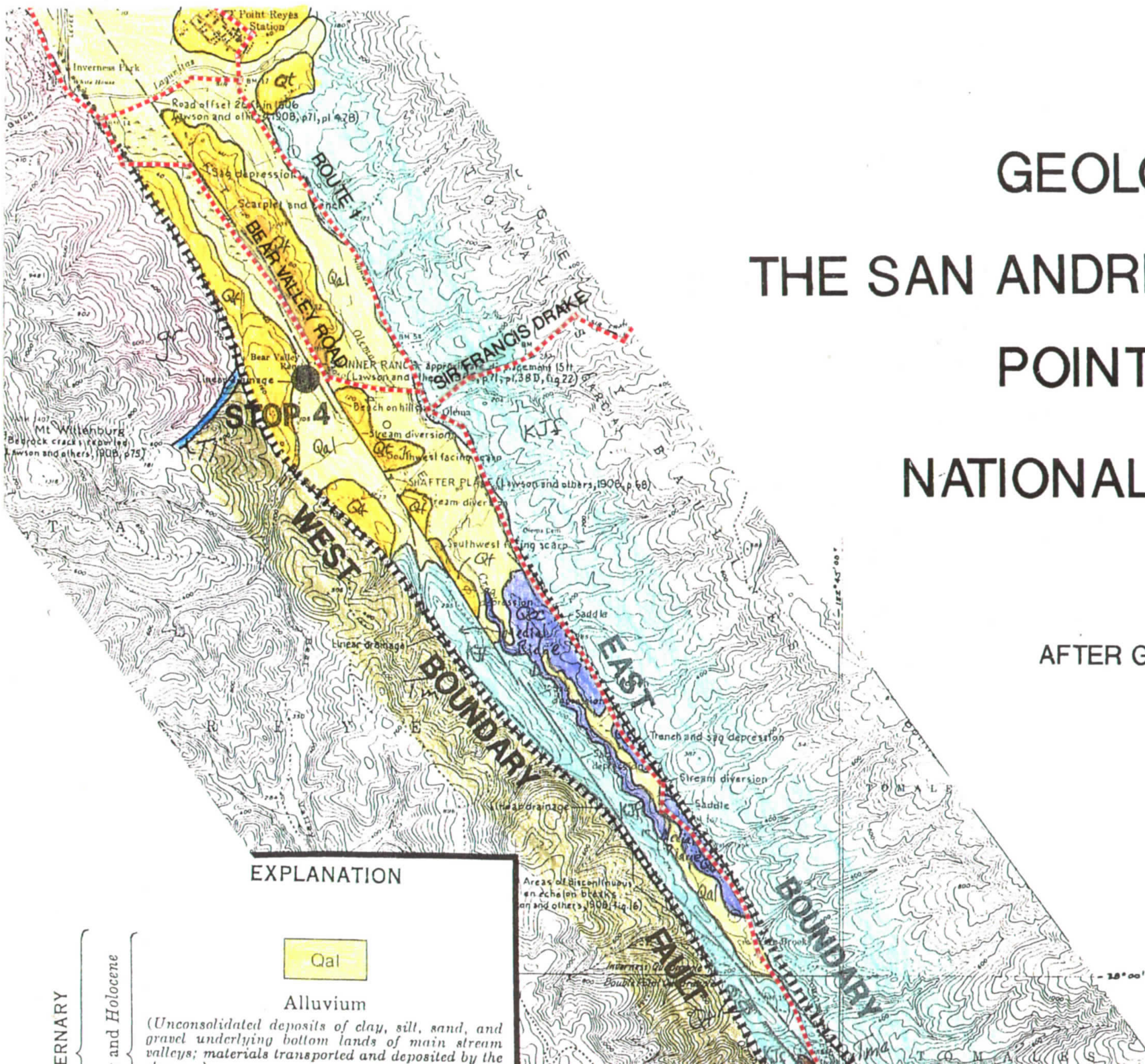


Figure 14. Aerial photograph of San Andreas Fault zone looking northwest from Bolinas.

GEOLOGY OF THE SAN ANDREAS FAULT ZONE, POINT REYES NATIONAL SEASHORE

AFTER GALLOWAY, 1977 AND PAYNE, 1967



QUA[TERNARY] — *Pleistoce[ne]*

Qt

Terrace deposits

(Unsorted and unconsolidated rock fragment debris deposited on stream and wave cut surfaces.)

Qoc

Olema Creek Formation

(Lake beds in the San Andreas fault zone. Chiefly light blue-gray clayey siltstone or claystone, thinly laminated, with interbeds of coarse granitic gravel. Contains peaty layers in places.)

Qm

Millerton Formation

(Marine and nonmarine beds of clay, silt, sand, and gravel in the San Andreas fault zone flanking Tomales Bay.)

TERTIARY — *Plio-Pleistocene*

Tmc

Merced Formation

(Blue-gray siltstone and soft, easily erodible, brown to tan sandstone, pebbly in places.)

TERTIARY — *Miocene*

Tm

Monterey Shale

(Mainly thin-bedded to massive, gray to brown organic shales, and thin bedded, commonly highly contorted cherts. Contains sandstone beds in a few places.)

Tl

Laird Sandstone

(Typically massive, medium- to coarse-grained, poorly cemented, light brown sandstone.)

JURASSIC - CRETACEOUS

gr

Granitic rocks

(Mainly quartz diorite, granodiorite, and adamellite.)

Kc

Calera limestone

(Tectonic blocks of fine-grained limestone in the San Andreas fault zone.)

KJf

Franciscan rocks, undifferentiated

(Disrupted and sheared graywacke, shale, conglomerate, chert, and serpentine in and near the San Andreas fault zone)

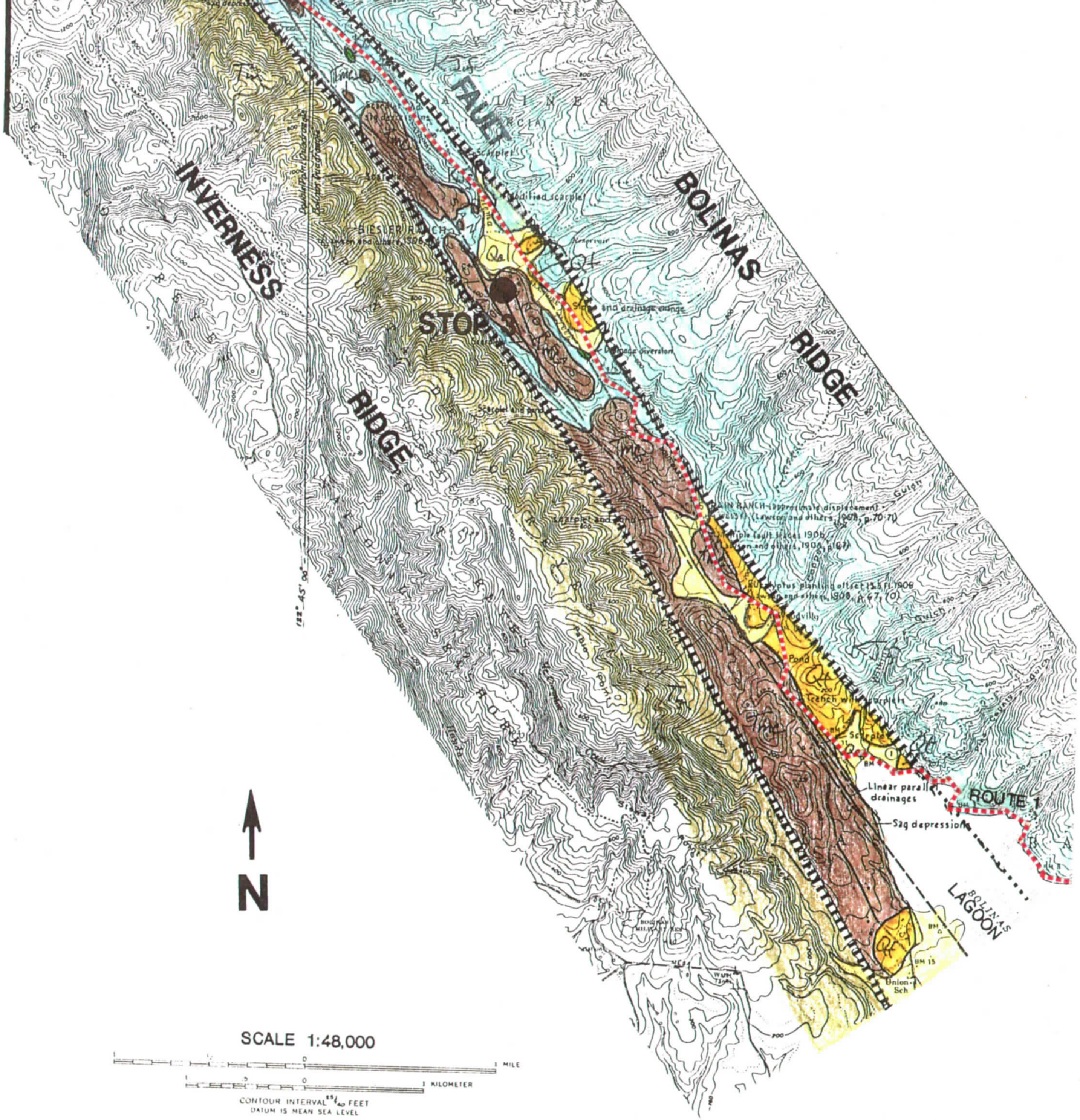


FIGURE 15

STOP 3

GOVERNMENT HOUSING AT RANDALL TRAILHEAD

by Stephanie Davis

At this stop you will see excellent examples of landforms produced by motion along the strike-slip San Andreas Fault: sag ponds, linear ridges and valleys, and scarps. Also exposed are Pliocene to Pleistocene sediments deposited in basins bounded by the fault or in the fault zone itself.

Walk down the driveway between the houses. Turn right before the barn and left just before the corral. Head back along the dirt road toward Inverness Ridge.

Just beyond the corral on the left is a large pile of tan siltstone from the Plio-Pleistocene Merced Formation. The Merced here lies unconformably on top of the Franciscan and was deposited in a restricted bay environment. The hill on which you are standing and the low hills immediately to the west are underlain by the Merced.

Continue west along the road until you come to a small sag pond on the right. You are now standing between the two strands of the 1906 rupture as mapped by G. K. Gilbert. The west strand runs along the base of the ridge on the west (left) side of the pond and continues through the hillside beyond. The east strand passes about halfway between the barn and the pond. The sag pond and associated ridges were created by earlier movements along the same strand of the San Andreas.

To the west, the steep forested Inverness Ridge is underlain by Monterey Shale and is west of the San Andreas, (i.e., part of the Pacific Plate). The west boundary fault lies in the gully between Inverness Ridge and the hill you're standing on.

To the east, the forested slopes of Bolinas Ridge are underlain by Jurassic-Cretaceous Franciscan Complex. The break in slope near the base of the ridge marks the trace of the east boundary fault.

The toe of the ridge directly opposite the houses is underlain by Pleistocene stream terrace deposits consisting of a poorly consolidated conglomerate of angular Franciscan clasts. The best exposures are about 100 feet south of the end of the driveway.

SAN ANDREAS FAULT

The trace of the San Andreas Fault is the one of the most prominent physiographic features of the Point Reyes region. The San Andreas Fault separates the Pacific Plate on the west from the North American Plate to the east (see Figure 13). The fault originated during post Early Miocene time (29 mybp) as a right-lateral transform. Bolinas Ridge to the east of the fault is underlain by the Franciscan Complex, a deformed assemblage of greywacke, shale, conglomerate, chert, and serpentine now connected to the North American Plate. On the west side of the fault zone, the Inverness Ridge is underlain by weathered Cretaceous granite and granodiorite of the Salinian Block and overlying Tertiary sediments. Cumulative displacement along this portion of the San Andreas is about 455 km (Clark and others, 1984), yielding a slip rate of about 1.6 cm per year.

Geomorphology of the Fault Zone

The San Andreas Fault is expressed topographically as Olema Valley, a linear trough .8 to 1.6 km wide and 21 km long that separates the Point Reyes Peninsula from the mainland. The north and south ends of the trough are inundated by the Pacific Ocean, forming Tomales Bay and Bolinas Lagoon respectively.

A number of fault-related geomorphic features are evident in the Olema Valley (see Figure 15). The most prominent features are shutter ridges, elongate ridges parallel to the fault and so-named because they shut off the ends of drainages entering the fault zone. Parallel to the shutter ridges are linear troughs, many of which contain sag ponds (enclosed swamps and ponds).

Disrupted drainage patterns are very common within the fault zone. Olema Creek flows northwestward into Tomales Bay and Pine Gulch Creek flows southeast into Bolinas Lagoon. For approximately 3 km between Benchmarks 366 and 476 (southeast of Five Brooks) these creeks are parallel and flow in opposite directions separated by shutter ridges. Pine Gulch Creek, instead of directly entering the northwest end of Bolinas Lagoon, is diverted by a shutter ridge near the town of Woodville and enters the Lagoon approximately two miles to the south. Also many of the tributary streams feeding these two creeks are offset in a right lateral sense upon entering the fault zone (see for example Pine Gulch Creek tributaries near Woodville and Olema Creek feeder streams near Five Brooks).

Other geomorphic features found within the fault zone include side hill ridges, scarps, and hot springs.

Fault Trench Sediments

The bulk of the material occupying the fault trough at Point Reyes consists of strongly deformed Franciscan. Within the sheared matrix of the Franciscan are several blocks of Calera Limestone, the nearest known outcrop of which lies 50 kilometers south in San Mateo County. Deposited unconformably on top of this basement is a sequence of four stratigraphic units. Deposition of this sequence was largely controlled by movement along the San Andreas Fault and by the development of the fault trough.

The Merced Formation, which crops out within much of the southern half of the trough, consists of blue-gray siltstone and soft brown to tan sandstone. To the north, the Merced is found near Dillon Beach where it unconformably overlies the Franciscan. To the south the type section of the Merced is found at Seven Mile Beach, south of San Francisco. The Merced was deposited during the Middle Pliocene to Early Pleistocene as a shallowing-upward sequence within a restricted bay. During deposition, the Point Reyes Peninsula probably lay to the west at the latitude of the present Golden Gate. Subsequent northward movement of the peninsula has truncated the Merced Formation along the west side of the fault trough. The Merced is not found west of the fault.

The Pleistocene Millerton Formation crops out on the east side of Tomales Bay northwest of the town of Millerton and at Tom's Point near the entrance to the bay. It consists of up to 20 meters of marine and nonmarine clay, silt, sand, and gravel. The Millerton Formation is found only within the fault zone and was probably deposited in a restricted body of water comparable to the modern Tomales Bay.

The Pleistocene Olema Creek Formation is restricted to the central part of the fault zone between Five Brooks and Olema and is probably in part contemporaneous with the Millerton Formation. The Olema Creek Formation consists of at least 200 meters of light blue-gray, thinly laminated clayey siltstone, and claystone interbedded with coarse granitic gravel. Organic matter in the form of peat, woody material, and tree trunks is abundant. Fresh water diatoms of Holocene age are numerous. The Olema Creek Formation was deposited in a freshwater lake environment which occupied part of the San Andreas fault zone.

Pleistocene stream terrace deposits occupy both the northwest and southeast ends of the fault trench. These sediments unconformably overlie the Franciscan and Merced Formations and consist of poorly consolidated coarse sand, gravel, and conglomerate. Subsequent movement along the San Andreas Fault has deformed these sediments; dips of up to 15° have been recorded at the head of Bolinas Lagoon.

1906 San Francisco Earthquake

At 5:13 a.m. on April 18, 1906, a magnitude 8.3 earthquake jolted the Bay Area. The epicenter was located just west of the Golden Gate along the San Andreas Fault. Surface rupture occurred along 430 km of the fault trace from near Cape Mendocino south to San Juan Bautista. Maximum horizontal offset was approximately 6 meters in Marin County; vertical displacement was less than 1 meter.

Maximum intensity of the shaking was X-XI on the Modified Mercalli Scale. The high intensity shaking was restricted to within a few tens of kilometers of the fault. However, the felt zone was extremely large, ranging from Oregon on the north to Los Angeles in the south and east to Winnemucca, Nevada. Damage was widespread between Salinas and Eureka and was particularly severe in San Francisco. Structures built on fill, particularly bay mud, were the hardest hit. The subsequent fire in San Francisco caused even more damage than the quake and contributed to the tremendous loss of life; 315 deaths were reported in San Francisco and 700 lives were lost statewide.

Subsequent to the earthquake G. K. Gilbert explored the fault zone in Marin County and mapped many of the newly-formed geomorphic features. His observations may be found in Lawson and others (1908).

In 1979 a series of trenches was excavated at Dogtown to document the recurrence interval of events of the magnitude of the 1906 rupture (Cotton and others, 1980). At least four previous earthquakes were documented to have occurred at the Dogtown site with an average recurrence interval of 350 years. Statistically speaking, we're not due for the next biggie until 2256 A.D.!

ROAD LOG

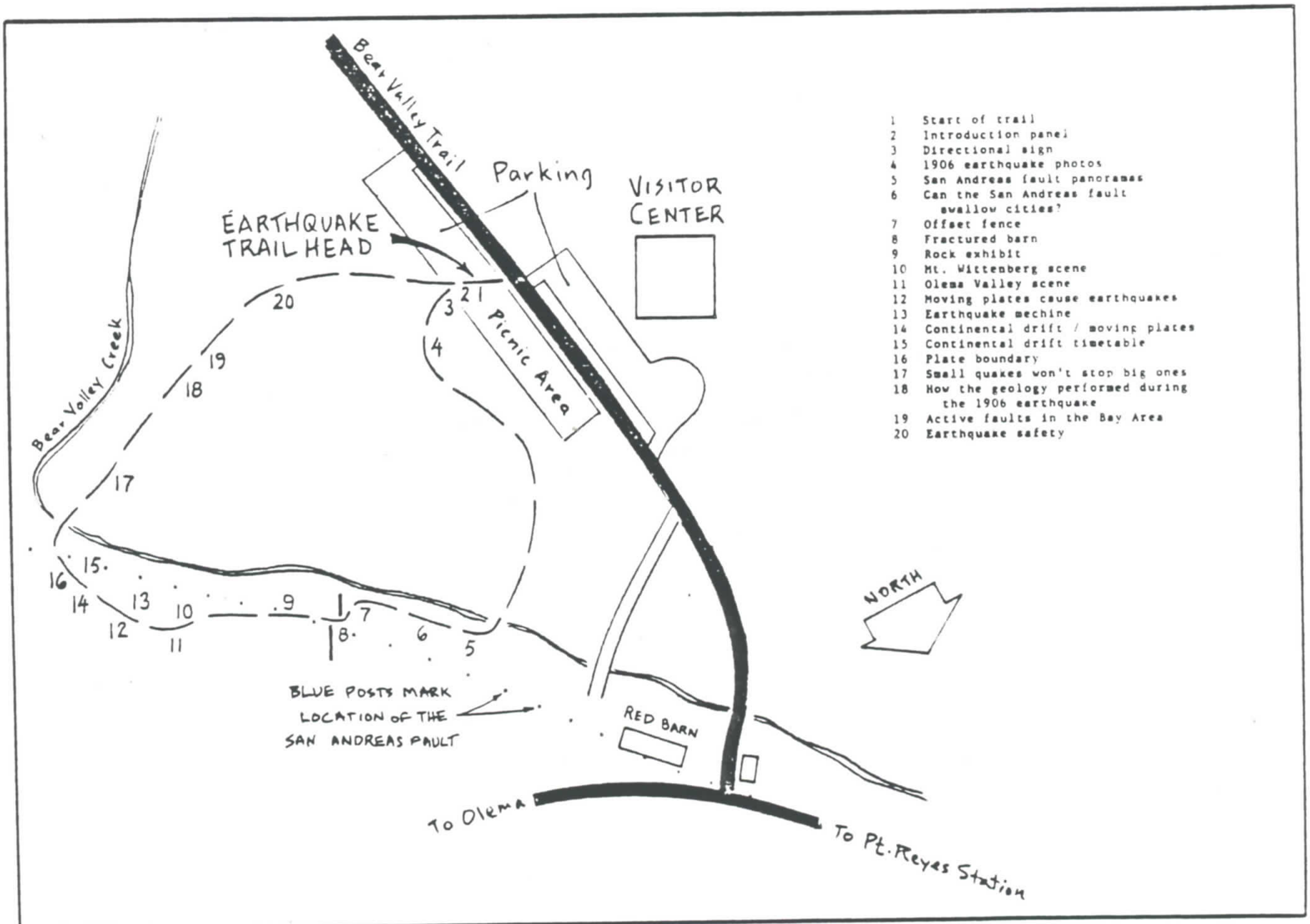
Return to the cars and head north to Point Reyes National Seashore Headquarters. At the stop sign in Olema go straight, back the way we came. After a tenth of a mile turn left on Bear Valley Road toward Point Reyes National Seashore Visitor Center. Just past the sign for the National Seashore near the red barn we cross the last-active strand of the San Andreas Fault. The trace is marked by a series of blue posts set into the hillside beyond the barn.

Turn left into the Visitor Center parking lot.

THE EARTHQUAKE TRAIL

AT

POINT REYES NATIONAL SEASHORE HEADQUARTERS



(MCCLELLAN. 1986. AFTER HALL. 1981)

Figure 16. Sketch map of Earthquake Trail at Bear Valley Visitor Center.

STOP 4

POINT REYES VISITOR CENTER

by Stephanie Davis

The headquarters of the Point Reyes National Seashore occupies the site of Skinner Ranch. G. K. Gilbert was able to map four displaced cultural features on the ranch to document the 4 to 5 meter offsets produced here by the 1906 earthquake. Although most of these features are gone today, the "offset fence" has been reproduced on the Earthquake Trail.

The Earthquake Trail (see Figure 16) is located off the dirt parking area across the road from the visitors center. The present trail was constructed between 1972 and 1976 by N. T. Hall and a number of geology students from Foothill College. The exhibits along the trail explain the San Andreas Fault and general geology of Point Reyes in terms of the plate tectonic model. In addition, the displays interpret the fault-associated landforms and describe how earthquakes affect people and what can be done to prevent or reduce earthquake damage. The trail is paved and takes 15 to 20 minutes to circumnavigate.

Also, be sure to see the Visitor Center. There you will find interpretive material both on display and for sale. The rangers can provide much additional information. The dioramas and raised relief map should not be missed. You can also view a 20 minute film on the natural and cultural history of Point Reyes.

If you have any free time during lunch, read the article on Marine Mammals below to give you an idea of what you might look for at our next stop at the beach.

MARINE MAMMALS

by Mary Rose Cassa

One of the most popular aspects of Point Reyes National Seashore is its marine mammal population. Harbor seals are frequently seen and heard in the esteros and Tomales Bay and sea lions can be seen sunning themselves on rocks off the coast. By far the most spectacular marine mammals that can be seen at Point Reyes, however, are the gray whales. Point Reyes is one of many promontories along the California coast where the migrating whales may be sighted.

Whales

Cetaceans (from Greek word ketos, meaning "whale") are among most mobile creatures in the world. Populations of large whales move poleward in summer and southward toward the tropics in winter. Most of this movement is presumably related to the availability of generous food supplies in polar seas in summer and the relative warmth and calmness of tropical seas in winter. The seasonal movements of gray whales and humpback whales, year after year, constitute migration in the precise biological sense (Leatherwood and Reeves, 1983). Other species, though less predictable, seem to undertake seasonal relocations to avoid extremes of heat and cold, remaining in regions that provide adequate food supplies.

The closest one can usually see a whale is when they stray into shallow water (as did "Humphrey" in 1986). Little is known about this phenomenon called "stranding", where solitary whales swim into bays and estuaries or singly or in groups beach themselves. One hypothesis holds that the animals simply "miscalculate" while following prey or avoiding predators. Another hypothesis is that parasite infestations may interfere with the whales' bio-sonar navigational system or sense of equilibrium.

Often the blow, or spout, is the first, and only, sight that one gets of a whale. The plume of vapor is composed of water and oil from the whale's breathing passages that is forcefully exhaled as a fine spray when the animal surfaces to breathe. The height, shape, and direction of the blow are characteristic for each whale species (see Figure 17).

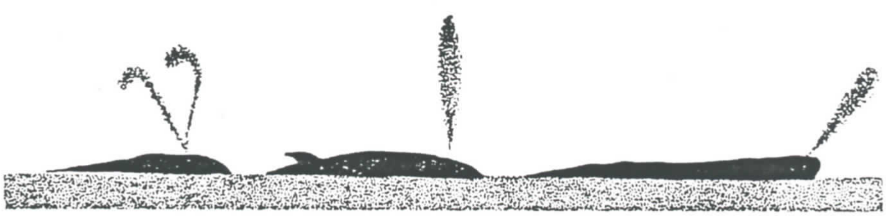


Figure 17. From left to right, the blows of a right whale, fin whale, and sperm whale (from Burton, 1973).

More people have seen gray whales (suborder Mysticeti or baleen whale) than any other species. Each year thousands of gray whales migrate along the shallow waters off Washington, Oregon, and California, where they can be seen from coastal cliffs. In one of the longest known migrations for any mammal, gray whales travel from the Bering and Chukchi seas to calving grounds in shallow lagoons and protected bays along west side of Baja California. The annual migration of the California stock supports a significant whale watching "industry" from November through March, although small bands of gray whales have been observed during all seasons near the Farallon Islands.

We know more about gray whale migrations than we do about the movements of any other species because they stay close to land, particularly during their southward migration. Staying inshore of the 100-fathom contour and passing close to promontories and across the mouths of bays, these whales may navigate by following ocean-bottom contours, offshore islands, and promontories. The procession is always led by older whales, suggesting that a learning process may be involved (Gardner, 1984). The major parts of the migration take about six weeks to pass a given point, with the main body passing during the middle three weeks (early to mid-December for the San Francisco area; Miller, 1975). First to appear are pregnant females, followed by nonpregnant females and males. Young calves grow rapidly in the warm waters off the west coast of Baja California and are ready to travel north with their mothers by March. Newly pregnant females begin the trip northward in February, followed by adult males and immature whales of both sexes.

Gray whales appear mottled gray because of the barnacles and "whale lice" (crustaceans) covering their otherwise dark-colored skin. The blow, from two external blowholes, is low and puffy. Their present range is limited to the North Pacific Ocean.

Humpback Whales. The humpback whale, also a baleen whale, is easily recognized by its stocky body, enormous flippers, and numerous knobby protuberances. Humpbacks characteristically raise their serrated tail flukes before sounding (diving), and they have the distinctive habit of occasionally leaping entirely out of the water and landing with a great splash. No large whale species is more animated or acrobatic than the humpback. Humpbacks, like grays, undertake very regular migrations, spending summers as far north as the Arctic Ocean and moving far southward in the breeding season. One southward path takes them to Hawaiian waters, another to the area off southern California (Gardner, 1984). The blow of the humpback whale is 2.5 to 3 m tall and bushy.

Carnivores

Only three marine carnivores are commonly seen at Point Reyes. They are the California sea lion, the northern or Stellar's sea lion, and the harbor seal. Sea otters were once especially abundant around the Farallon Islands, but they seem to spend their entire lives at sea and are seldom seen even on offshore rocks along the California coast.

Seals and sea lions belong to the order Pinnepedia. California sea lions and Stellar's sea lions are eared seals (family Otariidae). Their hind flippers can be brought under the hind part of the body and used for locomotion on land. The nails of the three middle digits of the hind flippers are well developed. Their external ears, although not large, are easily seen. The front flippers are proportionately large and naked and are the primary means of propulsion.

California sea lions are common zoo and circus animals. They are the most abundant and most commonly seen pinnipeds along California coast.

Their smaller size and staccato, barklike calls readily distinguish them from Stellar's sea lions with which they often associate. Individuals can be seen resting on isolated sandy beaches of Point Reyes. Unlike California sea lions, Stellar's sea lions do not habitually enter bays, estuaries, or river mouths.

Harbor seals are earless seals or hair seals (family Phocidae). Their hind flippers cannot be brought under the body and used for locomotion on land. Nails are equally developed on all five digits. The front flippers are relatively small, with well developed claws, and play an insignificant role in propulsion. Harbor seals often come into bays and estuaries and may be seen resting on sand bars at low tide. They are notably silent in contrast to many other pinnipeds.

Facts About Whales

- The tongue of a blue whale weighs as much as an elephant.
- The gray whale migrates more than 10,000 miles each year.
- One humpback whale may carry half a ton of barnacles on its skin.
- Whales have no vocal cords; yet they can make sounds under water without releasing any air. The low-frequency sounds emitted by some large baleen whales can be heard 1000 miles away.
- Convergent evolution has led to a similar mouth design for both baleen whales and flamingos. Both have a narrow upper jaw and a large fleshy tongue in a deep lower jaw designed to cover a filtering mechanism that separates food from water.
- Toothed whales have a single blowhole; baleen whales have two blow holes.
- Whalebone is not bone. It is the baleen found in a whale's mouth and is made of keratin, the same material found in your fingernails.

From Gardner (1984): <u>The Whale Watcher's Guide</u>

ROAD LOG

<u>Head back toward Bear Valley Road, the way you drove in</u>.

<u>Turn left onto Bear Valley Road</u> from the park headquarters toward the Beaches. Note the concrete monument in the front lawn of the house on the left. This is one of four monuments installed by the State Earthquake Investigation Commission in 1906 to measure future movements along the

1906 trace. The iron cap on the monument protects a brass plate designed to hold in a fixed position a Fauth theodolite from U.C. Berkeley's Engineering Department. No movement has been recorded along this part of the San Andreas since 1906.

Just a little way past the turn, note the sag pond on the right. The 1906 trace lies to the left of the road.

Limantour Road to the left. Multiple strands of the 1906 rupture are on the medial ridge to the right. From the top of the ridge a number of small fault-related land forms may be observed, in addition to a spectacular panoramic view of the fault zone, Tomales Bay, and Pleistocene wave-cut terraces. You can park on the right shoulder near the road to the Bear Valley stables and hop the fence for the view! Limantour Road leads to Limantour Beach. It was named for José Yves Limantour, a French trader from Mexico who ran his ship aground on the beach. His name was once applied to Drakes Estero, but was changed after Limantour was convicted of land fraud in 1858.

Intersection with Sir Francis Drake Blvd. Turn left onto Sir Francis Drake Blvd.

About 0.7 miles after the turnoff you enter Inverness Park. The salt marsh of Tomales Bay is on the right, past the little settlement. Deep water extended up to here in the early 1800s but has filled in with sediment because of disturbance of the watershed.

1.5 miles after entering Inverness Park, look for Redwood Ave. on the left. The house barely visible through the trees suffered during the great mudflows of the winter of 1981. The owner has built a concrete diversion wall upstream of the house in an attempt to lessen the damage from any future storm. A discussion of the mudflows follows.

EARTH FLOWS IN INVERNESS AND ELSEWHERE IN THE BAY AREA

by Chuck Kluth

Earth flows are a common, and often destructive feature in the Bay Area. They are easy to identify, with their dish-shaped breakaway scars, hummocky topography, tongue or tear-drop shape and bulging toes (see Figure 18). Flows generally form in fine-grained, relatively unconsolidated material that loses strength as its water content increases. The risk of earth flows increases on slopes greater than approximately 8°-10° (Keefer and Johnson, 1983).

Large areas of Marin County are underlain by Franciscan melange, composed of soft, sheared mudstone, ideal for the formation of earth flows. The occurrence of seasonal (winter) rains that can come in large storm events further enhances the conditions for earth flows. That is why earth flows are so common in the hills of Marin County and elsewhere in the Bay Area (Keefer and Johnson, 1983, Rogers, 1986).

The water reduces the strength of the material, and reduces the effective stress that holds fractures and shear surfaces together. When that effective stress is lowered beyond a critical value, shear failure occurs along planes that bound the flow and the material moves. The surface of most active flows will not support a person's weight. Striated surfaces are common features along the margins of the flows (Keefer and Johnson, 1983). The idea of a reduction of effective stress by addition of water also has been applied to the movement of thrust faults, but the original concept came from soil mechanics.

Several major winter storms swept over the Bay Area in late 1981. The Marin County region already had over 24 inches of rainfall for the season when another cold front stalled over the coastal mountains and dropped as much as 24 inches of rain in some areas in approximately 32 hours. The torrential rainfall triggered flooding, and thousands of debris and earthflows in the saturated hills. At Love Creek, north of Santa Cruz, a slide of more than half a million cubic meters buried nine homes and killed ten people. In general though, the flows were smaller and less destructive (McClellan, 1986, Ellen and Wieczorek, 1988).

In the village of Inverness, through which we pass on the west side of Tomales Bay, flooding and debris flows caused considerable damage in January, 1982. Large flows originated in valleys west of the village and rapidly moved into Tomales Bay. Three houses were destroyed, and 50 were severely damaged, including those filled with mud. Several houses were washed into Tomales Bay. The local water system was destroyed and telephone and electrical systems damaged. The floor of First Valley was covered by up to one meter of mud, sand, rocks and debris. Losses in Marin County included 5 dead, 379 injured, approximately $65 million in private and $15 million in public property (McClellan, 1986, Ellen and Wieczorek, 1988).

Today there are no obvious signs of the disaster. Many residents have erected retaining/diversion walls in order to mitigate future hazards.

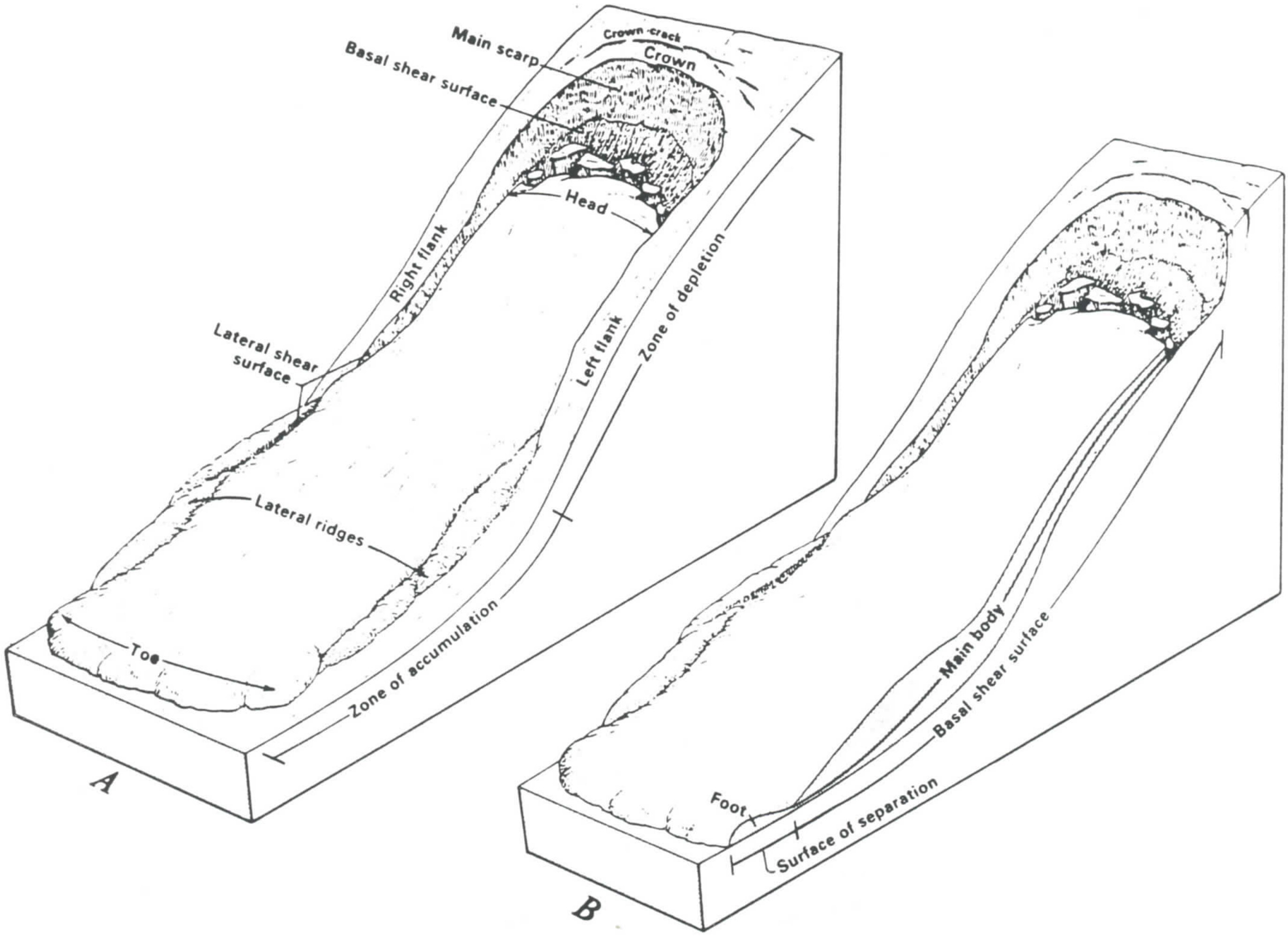


Figure 18. Generalized features of an earth flow. Many examples of this morphology are present in the East Bay and throughout the San Francisco area (from Keefer and Johnson, 1983).

About 2.5 miles from Inverness Park is the tiny town of Inverness. The ridge off to the left is Inverness Ridge. It is made of Salinian granite which has been correlated to granite exposed east of the San Andreas Fault in the Transverse Ranges north of Ventura.

The road turns to the left and begins to climb Inverness Ridge. The forest here consists mainly of Bishop pines. Farther south along the ridge the forest is dominated by Douglas Fir. The Bishop pines prefer the granitic soil of the northern end of Inverness Ridge. They are closed-cone pines, which require periodic fires to open the cones and release the seeds. The trees are relatively short-lived, and a hiatus of 80 years between fires could result in the destruction of the forest after a devastating fire (Evens, 1988).

Just past the Point Reyes National Seashore sign, there is a "Y" intersection. Take the right fork onto Pierce Point Road.

Tomales Bay State Park. Here the roadcuts expose Laird Sandstone, a transgressive sand deposited on an eroded surface of the granite.

Continuing on, Drakes Estero is soon visible off to the left. There are several arms of the estero; this one is named Schooner Bay for the ships that landed here to take on cargos of butter bound for San Francisco. Abbotts Lagoon is visible off to the right, near the beach.

Just past the Abbotts Lagoon parking area, Monterey outcrops are visible on the right. The diatomaceous sediment weathers to a white color.

About 2.2 miles past Abbotts Lagoon is the Kehoe Beach parking area. Pull over to the right and park for Stop 5.

STOP 5

KEHOE BEACH

Kehoe Beach offers us a great opportunity to study the stratigraphic section of the peninsula from the granitic basement to the basal part of the Monterey. The rocks are dramatically exposed in tall cliffs along the beach. A short description of the rocks visible here and a discussion of beach processes follow this introduction.

This is a scenic place but please be careful. THE SURF IS DANGEROUS. The rip currents are strong and the waves generally break hard onto the beach. This is not a popular beach for playing in the surf, but beachcombing, and if we're lucky, sunbathing are enjoyable. Be careful near the cliffs as well, they are steep and the rock is commonly loose and could come down on your head. One can guess how much fun this place is during a plus high tide.

A short half-mile path leads down to the beach from the road. This is a good place for a pit stop because there are no facilities on the beach. The path passes a somewhat rare feature on Point Reyes Peninsula, a fresh water marsh. Here bog lupine grows in abundance with other freshwater marsh plants. Watch and listen for the bullfrogs and common yellowthroats that make their home here.

Where the path meets the beach, follow the cliffs to the right to see the exposure of the basal stratigraphic section. If the tide is low enough, tidepools may be exposed where one can inspect the wildlife.

LITHOLOGY AND STRATIGRAPHY OF ROCKS EXPOSED AT KEHOE BEACH

by Terry Huemer

At Kehoe Beach the following succession is exposed from bottom to top: granitic basement, Laird Sandstone, and Monterey Formation. The following description of these rocks as they occur in the Point Reyes area is taken largely from Galloway (1977). Refer to Figure 6 in Clark and others (1984) for a detailed stratigraphic column.

Granitic Basement

Granitic basement rocks of the Point Reyes Peninsula are exposed from Mt. Wittenberg northwestward along Inverness Ridge to Tomales Point. A separate exposure occurs at Point Reyes. Although the exposures are similar, it is not certain whether they are part of the same pluton. The granitic basement has a vertical thickness of about 300 meters between the highest exposure on Point Reyes Hill to the lowest

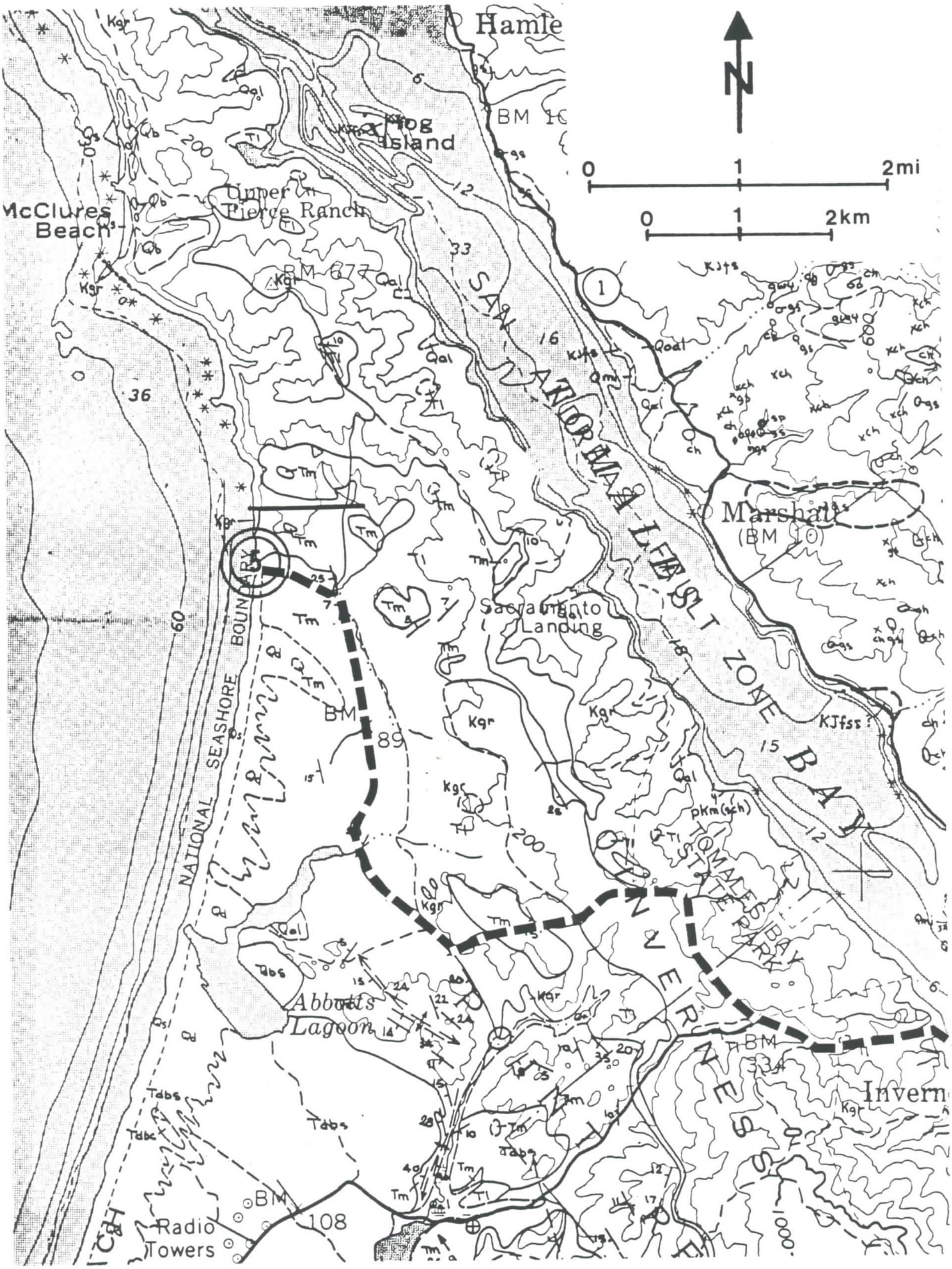


Figure 19. Geologic map of Stop 5. Map symbols: pKm-Metamorphic rocks embedded in granite, Kgr-Granitic rock of Point Reyes, Tl-Laird Sandstone, Tm-Monterey Formation, Tdbs-Santa Margarita Sandstone, Tdbc-Santa Cruz Mudstone and Purisima Formation, KJfs-Franciscan melange, sp-serpentinite, ch-chert, gs-greenstone, gwy-graywacke, Qmi-Millerton Formation, Qd-dune sand (from Blake and others, 1974).

exposure on Tomales Bay. At Point Reyes itself, over 150 meters of granitic rock is exposed.

Granitic outcrops at Tomales Point and Inverness Ridge have a composition ranging from quartz diorite through granodiorite and quartz monzonite. Granodiorite and quartz monzonite occur at Point Reyes. Pegmatites, aplites, and many other variations of these rock types crop out on the Point Reyes Peninsula. Fresh granitic rocks are typically gray, medium-grained, and form rounded or craggy outcrops. Due to deep weathering and dense vegetation, the best exposures are restricted mainly to the seacliffs.

Ross (1978) concluded that the emplacement of the plutonic rocks of Point Reyes and most of the rest of the Salinian block occurred in the Middle Cretaceous 100-110 million years ago. Intruded sediments were metamorphosed and subsequently eroded, resulting in scattered inclusion and roof pendants of schist, quartzite, calc-hornfels, and marble (Hall, 1981).

Laird Sandstone

The granitic basement of Point Reyes Peninsula is nonconformably overlain by various Tertiary marine sediments, the oldest of which is the Laird Sandstone (Hall, 1981). The Laird crops out along the western margin of the granitic basement exposure in the northern portion of the Inverness Ridge and extends from the vicinity of Kehoe Beach southeastward to Mt. Wittenberg. The sandstone is 60 meters thick in the type area west of Laird's Landing. It thins to the south but thickens again on the northern flank of Mt. Wittenberg.

West of Laird's Landing the Laird Sandstone is typically fairly friable, light brown, massive, medium- to coarse-grained sandstone containing subangular quartz grains with substantial silty interstitial material and common biotite and white feldspar grains. The base of the sandstone grades conformably upward into the Monterey Formation, with siliceous shale beds increasing in frequency higher in the section.

The Laird Sandstone is believed to be Miocene in age and in the type area, is derived from weathering of the granitic basement. It appears to have formed in a quiet transgressive sea which advanced over the irregularly eroded surface of the granite.

Monterey Formation

The Miocene Monterey Formation crops out from the vicinity of Kehoe Ranch southeastward to Duxbury Reef. It is about 2500-2700 meters thick near Bolinas and thins to the northwest due to erosion and overlap onto the granitic basement.

The Monterey Formation includes cherts, porcelanites, organic shales, and thin arkosic sandstones. These strata are generally thin-bedded, laminated, micaceous, weather to a whitish color, and often contain fish scales, plant remains, forams, and diatoms. The existence of petroleum is shown by oil-filled joints, although of the several exploratory wells drilled between 1865 and the early 1950s none proved to be commercially valuable (Hall, 1981).

Bramlette (1946) concluded that the bottom topography of the Monterey sea was similar to the deeper basins and shallow water divides off the present coast in the Channel Islands area. Depths probably ranged from the upper limits of the neritic zone to the edge of the continental shelf and temperature and rainfall conditions were probably similar to those existing in California today. Evidence from two deep exploratory wells in the Point Reyes Peninsula suggest that the Monterey was deposited in a basin which deepened southeastward and that sediment thickness probably increases to the south. Galloway (1977) suggests that the Point Reyes sedimentary area is a northward extension of the La Honda Basin.

POINT REYES BEACH

by Mary Rose Cassa

The eleven-mile expanse of beach from Point Reyes northward to Kehoe Beach, extending as far as the Russian River, is one of the most spectacular on the California coast. This section of coastline is characterized by exposed beaches, aligned parallel to the predominant swell direction, and "hooked bays", suggesting that there is minimal sediment input to the coast (Leslie, 1975). Sediment is introduced to this section of coast by the Russian River and by streams south of Bodega Head. The sediment moves south along the coast, eventually getting trapped on the northern side of headlands. Much of this trapped sediment is then moved inland by wind action, forming the active dunes at Salmon Creek and Dillon Beach, north of Point Reyes (see Figure 20). During periods of maximum runoff and erosion, the Davidson Current may flow northward along the coast as a shoreward, shallow, surface current. It is the major transporting agent for suspended sediment introduced to the ocean via streams.

Beach Building Processes

Along coastlines where there is minimal input of new sediment, as in the coastline between the Russian River and the southern extreme of Point Reyes Beach, the general configuration of the shoreline is controlled by predominant swell conditions (see Figure 20). At Point Reyes Beach, these long, low, regular waves are dominantly west-northwest, with a period of 12 seconds (Leslie, 1975).

Deviation from normal wave conditions (for instance, during storm periods or during non-predominant wave conditions) results in an oblique approach of breaking wave fronts to the beach face and generation of littoral currents (see Figure 21). Normally, beyond thirty feet below low-tide water level, ordinary water motion does not

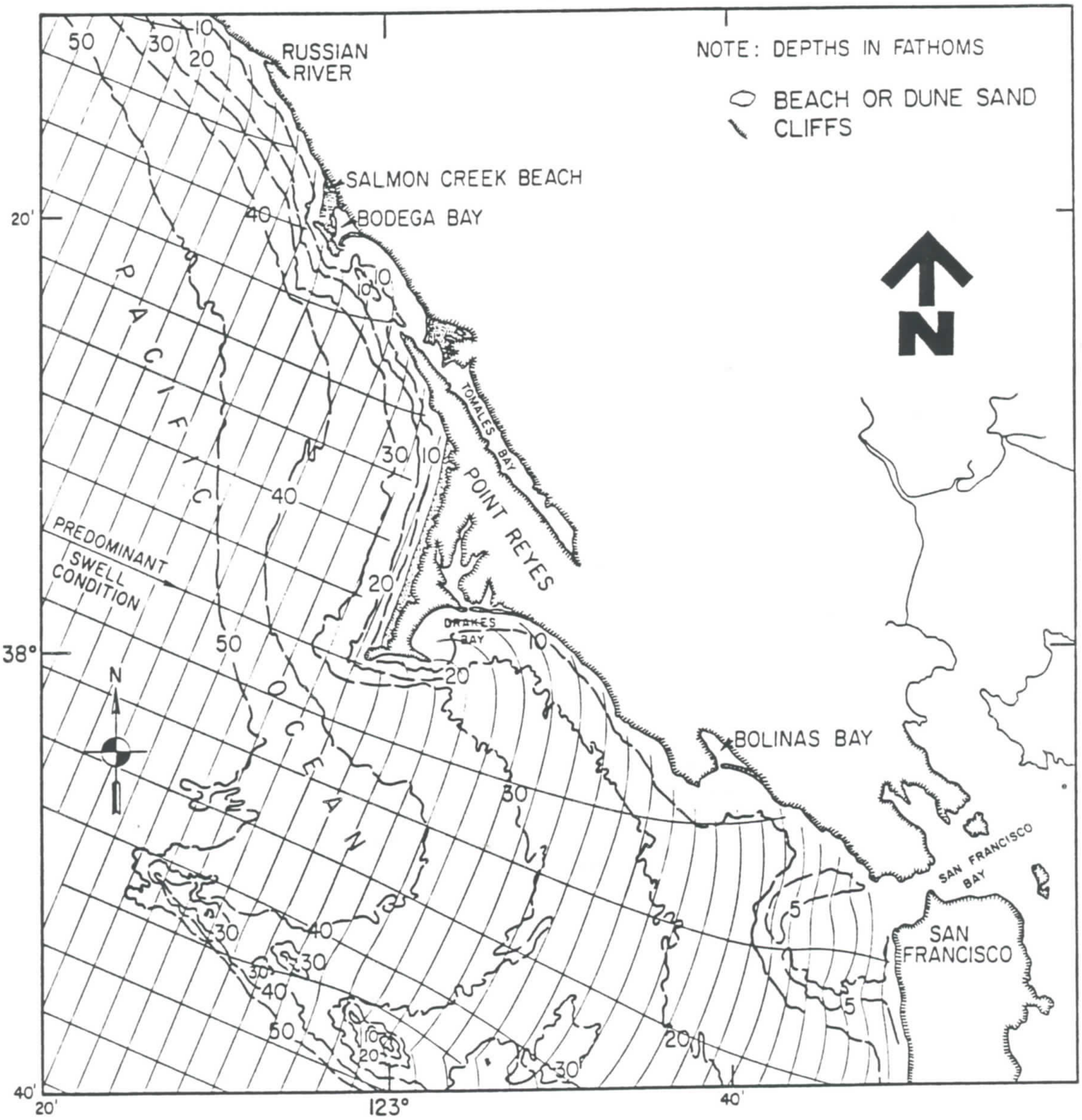


Figure 20. Wave refraction diagram in vicinity of Point Reyes. Scale = 1:600.000 (from Leslie, 1975).

have sufficient energy to move sand. In this zone, waves and currents provide the energy to keep sand in transit (Bascom, 1960). Littoral currents are strongest along continuous beaches when the alongshore flow is not interrupted by coastal headlands or embayments. Rate of transport is determined by wave energy, angle of wave attack, beach slope, and beach sediment characteristics. The shoreline is reshaped by scour, transport, and redeposition of beach sediment in a process that continues until the beach face becomes aligned with the breaking front. The extent to which the shoreline changes depends on the

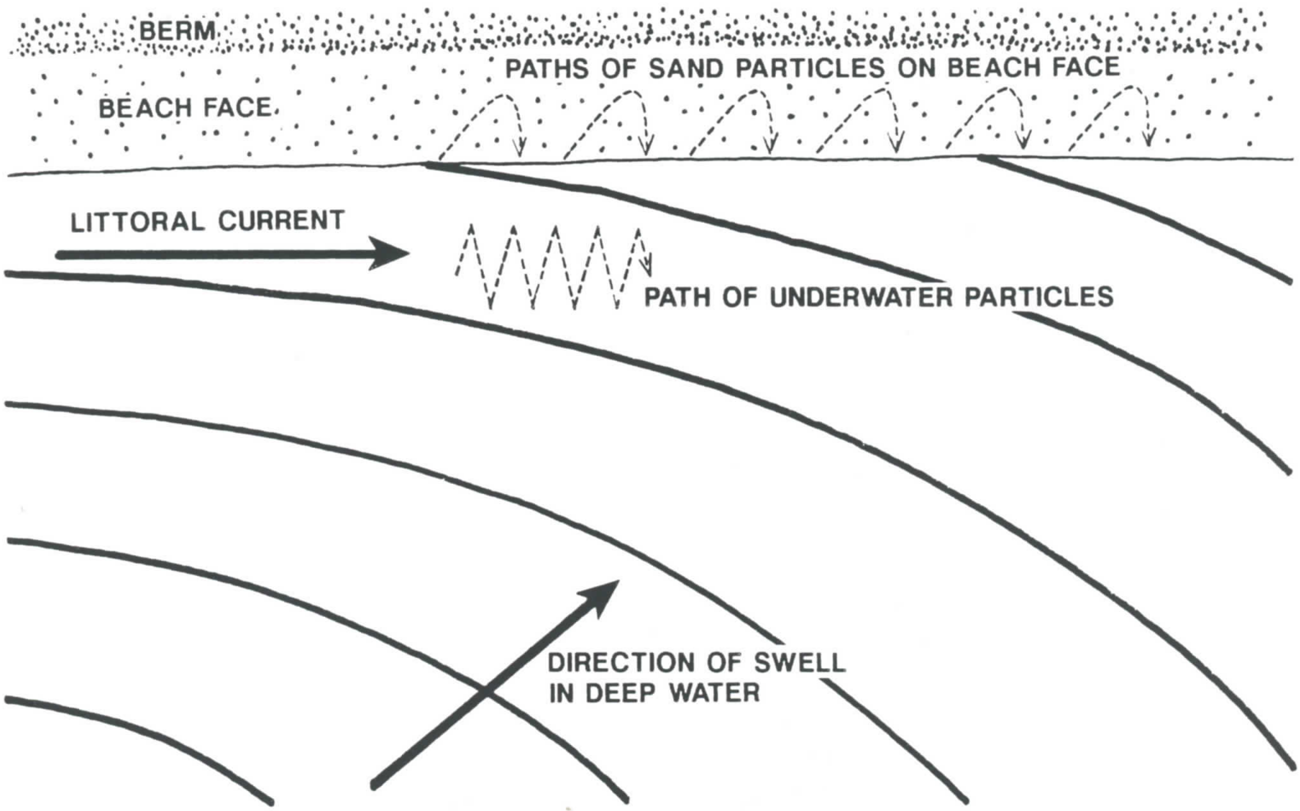


Figure 21. Diagrammatic map view of a beach. The littoral current, which runs parallel to the beach, is set up when waves approach the beach at an oblique angle. Sand grains are transported in the direction of the current (adapted from Bascom, 1960).

severity and duration of wave attack associated with non-predominant conditions.

In general, northern California beaches build seaward during summer months as sand from offshore is transported onshore by the action of long period swells. During winter months, the same beaches erode as steep storm waves provide sufficient uprush and return flow to scour beach sediment and relocate this material as bars in the offshore zone (see Figure 22). The seasonal cycle of accretion and erosion may cause a particular contour on the beach face to vary horizontally as much as 30 to 60 m during annual cycle (Leslie, 1975). After the storm season, the steepness of the waves decreases and they begin to move sand toward shore. The material from the outer bars fills in the troughs, and soon the beach profile shows no bars. Material from the inner bar migrates to the berm, building it seaward.

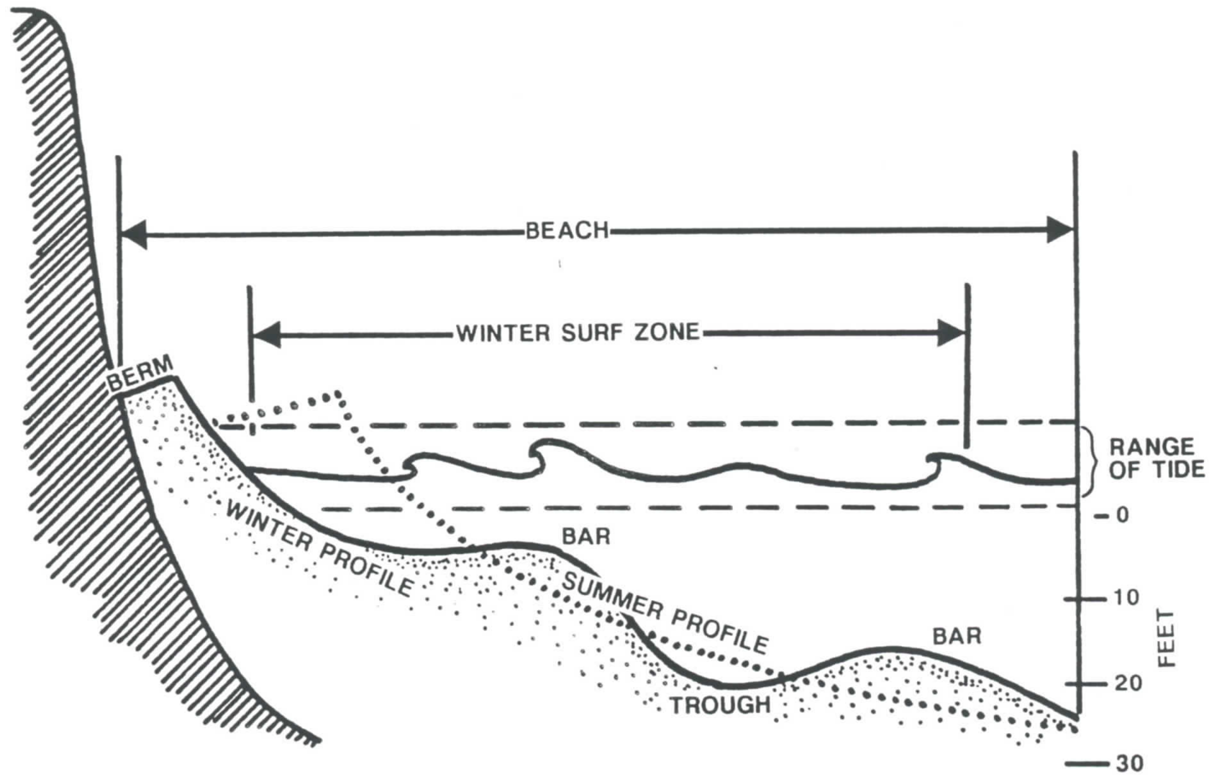


Figure 22. Beach profile, showing berm and bars. Heavy winter surf removes sand from berm and deposits it on bars. Lighter summer surf builds berm. Vertical scale exaggerated 25 times (adapted from Bascom, 1960).

A large part of the movement of beach material takes place as an exchange between offshore underwater ridges, or bars, and the berm, or the nearly horizontal deposit of material at the top of the beach onshore. Bars may be considered as products of erosion, since they appear when violent wave action cuts back the berm and deposits the beach material in offshore ridges. Because they are associated with storm conditions, and since more storms occur in winter than in summer, bars are regarded as a normal feature of the beach profile in winter. All beaches exposed to the ocean swell have bars, and beaches with a slope of less than 1 ft in 50 frequently have two or more (Bascom, 1960). When higher-than-average waves break in quick succession and raise the water level inside a bar, the water rushes back so energetically to sea that it sometimes breaches the bar at a narrow place, producing a so-called rip channel (Bascom, 1960). From then on much of the excess water thrown over the bar by the breakers moves along the beach until it reaches the channel where it flows out as a rip current. Because the flow is confined to relatively narrow channel a bather can get out of the current by swimming a short distance parallel to shore. On Pacific Coast beaches that are exposed to the full force of the waves, the top of the bar closest to shore is usually about a foot below the low-tide water level, the top of the second bar is at about seven feet, and the third bar is about thirteen feet deep (Bascom, 1960).

Cusps. Cusps are crescent-shaped depressions that occasionally form in regularly spaced series along the beach face. They vary in length from a few feet to hundreds of feet, and their relief may exceed 6 feet or be so shallow that they are barely discernible. There is no generally accepted explanation of how cusps begin, why they are so regular, or why they have the dimensions they have; however these factors are almost certainly related to the character of the waves that form them (Bascom, 1960).

Composition

Compositional categories of rock types encountered in the river, beach, and offshore deposits between Russian River and Point Reyes Beach include red chert, altered siliceous (nonred chert), porphyritic volcanics (welded tuffs), Pliocene volcanics (basaltic), other volcanics, granitics, vein quartz, greywacke, fine-grained siliceous (nonchert), and other material (shell fragments, schists, bottle glass, exotic rock fragments) (Leslie, 1975). The 4 to 10 mm size fraction of Russian River sediment is dominated by Franciscan material, principally greywacke, red chert, and vein quartz, and has a larger non-siliceous component than Point Reyes Beach material. From the Russian River to Point Reyes Beach, the relative proportion of nonsiliceous material decreases progressively from about 70% to 5 to 10% (Leslie, 1975).

The average compositional makeup of the 4 to 10 mm fraction is as follows (Leslie, 1975):

	Point Reyes Beach (11 samples) (%)	Point Reyes Offshore (3 samples) (%)
Red chert	29.7	16.5
Altered Siliceous	42.1	25.3
Vein Quartz	7.3	20.5
Fine-grained Siliceous	4.3	14.3
Greywacke	0.7	7.5
Granitics	2.3	1.3
Porphyritic volcanics	4.8	1.8
Pliocene volcanics	0.0	0.0
Green volcanics	0.9	2.3
Other volcanics	4.8	5.8
Other	2.4	4.7

The large proportion of Franciscan material in Point Reyes Beach deposits indicates that most of it was derived from the mainland east of Point Reyes Peninsula. The 4 to 10 mm fraction appears to be dominated by first-cycle material derived, transported, and deposited during the last interglacial cycle (Leslie, 1975). During periods of regression (lowering of sea level), the Russian River downcut through its alluvial channel, releasing large volumes of sediment to the coastal zone, and the sediment was transported southward. With rising sea level, a portion of the sediment was captured between Tomales Point and Point Reyes Head.

Beach Conservation

The major problems of beach conservation are created not by the seasonal movement of sand onshore and offshore, but by the motion of sand parallel to shore (Bascom, 1960). Alongshore or littoral currents can transport millions of tons of sand, eroding one beach and building up another. Large waves that approach the shore at an angle are often incompletely refracted, and the waves strike the shore at an angle. Where prevailing waves arrive in this way, a littoral current flows constantly. These currents are too slow to move sand grains by themselves, but turbulence in surf zone keeps the sand in suspension, and even low-velocity currents are able to transport large quantities of material. Sand particles carried up the beach face describe an arc in the direction of the alongshore current so that each wave moves them a little way along the beach in a sawtooth motion (see Figure 21). Sand travels downstream in a belt that is approximately the width of the surf zone. Any structure that interrupts the flow acts like a dam, and beaches immediately upstream grow while those downstream are stripped of sand by waves and currents.

ROAD LOG

After examining the cliffs at Kehoe Beach, our next cliffs to examine are at Drakes Beach, on the south side of Point Reyes Peninsula. Here it will probably be less windy and considerably warmer.

Drive back along the road southward. The hills just beyond Abbotts Lagoon are composed of Monterey Formation. The backside of the one on the right exposes the basal glauconitic sand of the Santa Margarita Formation which overlies the Monterey.

At the "Y" intersection of Pierce Point Rd with Sir Francis Drake Blvd, take a hard right. Follow the road toward Point Reyes.

About a mile past the Estero Trailhead you pass the northern end of Schooner Bay on the left. Farther on, Creamery Bay becomes visible off to the left.

Just before the turnoff to Drakes Bay you can see the western end of Point Reyes itself at about 1:30 o'clock.

At the intersection with the Drakes Bay Road, turn left toward Drakes Bay.

Shortly after the turn, the Park Service has installed a sign entitled, "The Pastoral Zone." The sign reads: "Six beef cattle ranches are operated within the seashore and run about 1800 head of stock. At present, the two most popular breeds are Hereford and Black Angus. Rather than raise the calf to maturity, most ranchers ship the calves to feedlots shortly after they are weaned. The seven dairies within the seashore milk about 3200 cows, producing over 5 million gallons of milk each year. The pastures produce only enough feed for about 5 months of the year. Feeding the milkers and the 2200 head of replacement stock requires trucking in 27,000 tons of feed each year. Most of the dairy operators in the area belong to milk cooperatives and sell directly to them.

"The legislation authorizing Point Reyes National Seashore in 1962 provided a seashore pastoral zone where the historical ranching and dairying scene would remain for future visitors. Arrangements were made during acquisition for the original owners to operate the ranches for periods of 20 to 30 years. Long term arrangements were necessary because of the large capital investments required to successfully operate a modern ranch or dairy."

As the road descends to Drakes Bay, the roadcuts on either side of the road expose Purisima Formation siliceous mudstones and siltstones. Park in the lot for Stop 6.

STOP 6

DRAKES BEACH

by Deborah Davis

The rocks that you will see at Drakes Beach, our last stop of the day, are made up of diatomaceous mudstones/siltstones of the Purisima Formation. There is a knee-deep lagoon between the parking lot and the beach which can be waded at high tide to get to the beach. Alternatively, you can take the path at the base of the cliffs to the left. Be careful, though, the rocks can be slippery. Be sure to visit the interpretive center on the east side of the parking lot.

As you walk east along Drakes beach you are approaching the axis of a low amplitude syncline. Notice also how the strata dip toward the east but that the high-angle normal faulting is down to the west. Also of note are small caves at the base of the cliffs where faults and large calcareous concretions are exposed. If you are really lucky and want to endure the constant rockfall, you may find fossilized whale vertebrae, starfish, etc., in some of the sandstone layers. The best pickings are far down the beach to the east. For those less daring, a fine example of a fossilized whale vertebra is on display at the Drakes Beach Visitor Center.

Purisima Formation

The strata exposed along the cliffs at Drakes Beach are part of the Purisima Formation, a basin-filling sequence deposited in the Bodega-Santa Cruz Neogene basin west of San Francisco. The basin is considered to be the offshore extension of the "Purisima Trough" of the Santa Cruz Mountains (Hoskins and Griffiths, 1971). The offshore extension of the basin is called the Bodega-Santa Cruz basin (see Figure 24).

Uplift of the Farallon ridge and compression along the San Gregorio Fault in the Middle to Late Miocene initiated the formation of the Purisima trough (Gavigan, 1984). Deposition of the marine sediments of the Purisima began in the latest Miocene or earliest Pliocene (6.0-4.9 mybp). Marine deposition ceased during the early Pleistocene because of general uplift along the central coast of California and final basin infilling (Gavigan, 1984).

The basin-filling sediments are an Upper Miocene and Pliocene sequence consisting of a transgressive shallow-water glauconitic sandstone unit known as the Santa Margarita sandstone overlain by the deep-water siliceous Santa Cruz mudstone followed by the diatomaceous mudstones/

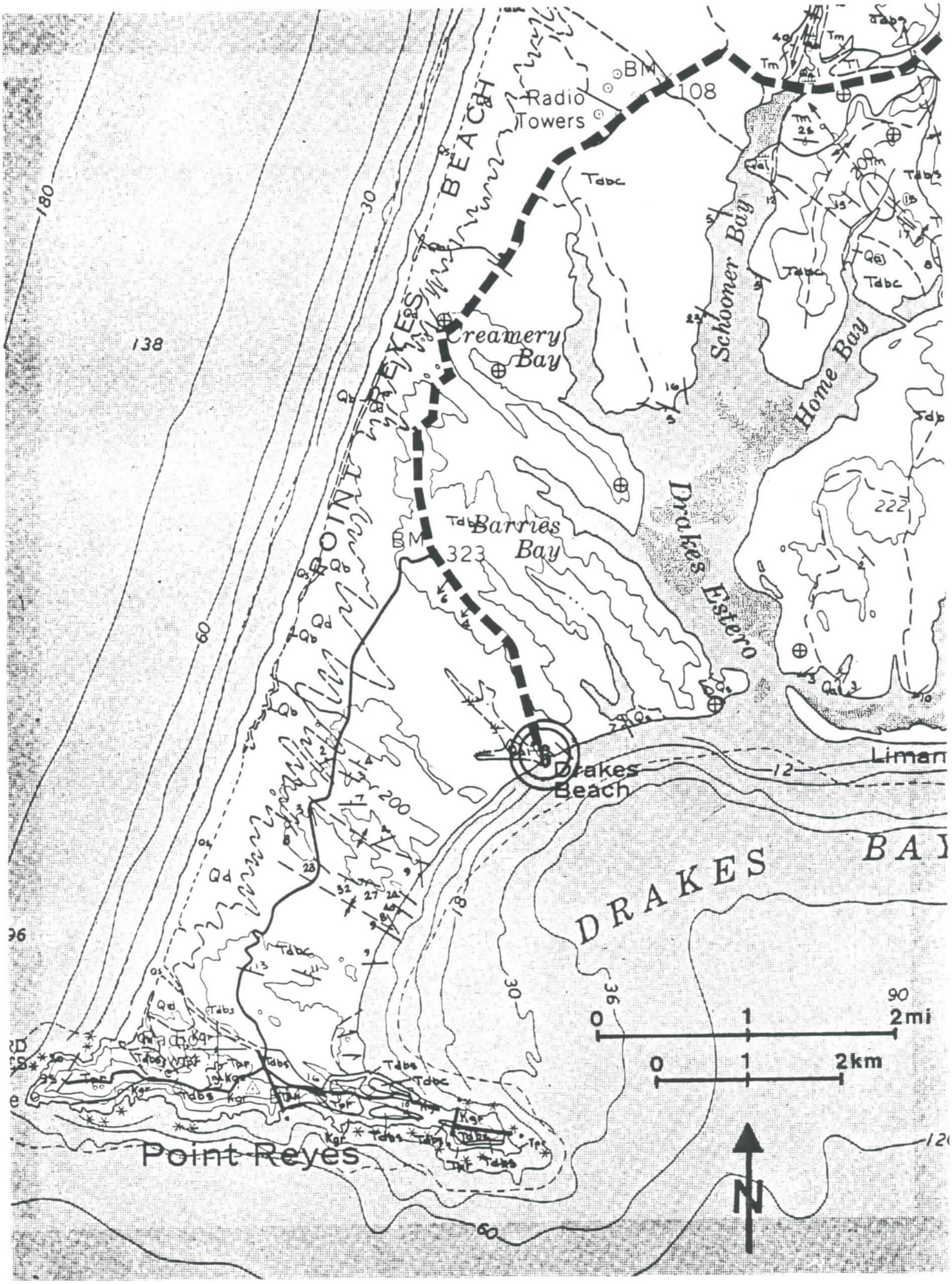


Figure 23. Geologic map of Stop 6. Map symbols: Kgr-Granitic rocks of Point Reyes, Tpr-Conglomerate at Point Reyes, Tl-Laird Sandstone, Tm-Monterey Formation, Tdbs-Santa Margarita Sandstone, Tdbc-Santa Cruz Mudstone and Purisima Formation, Qb-older beach sand, Qd-dune sand, Qs-beach sand (from Blake and others, 1974).

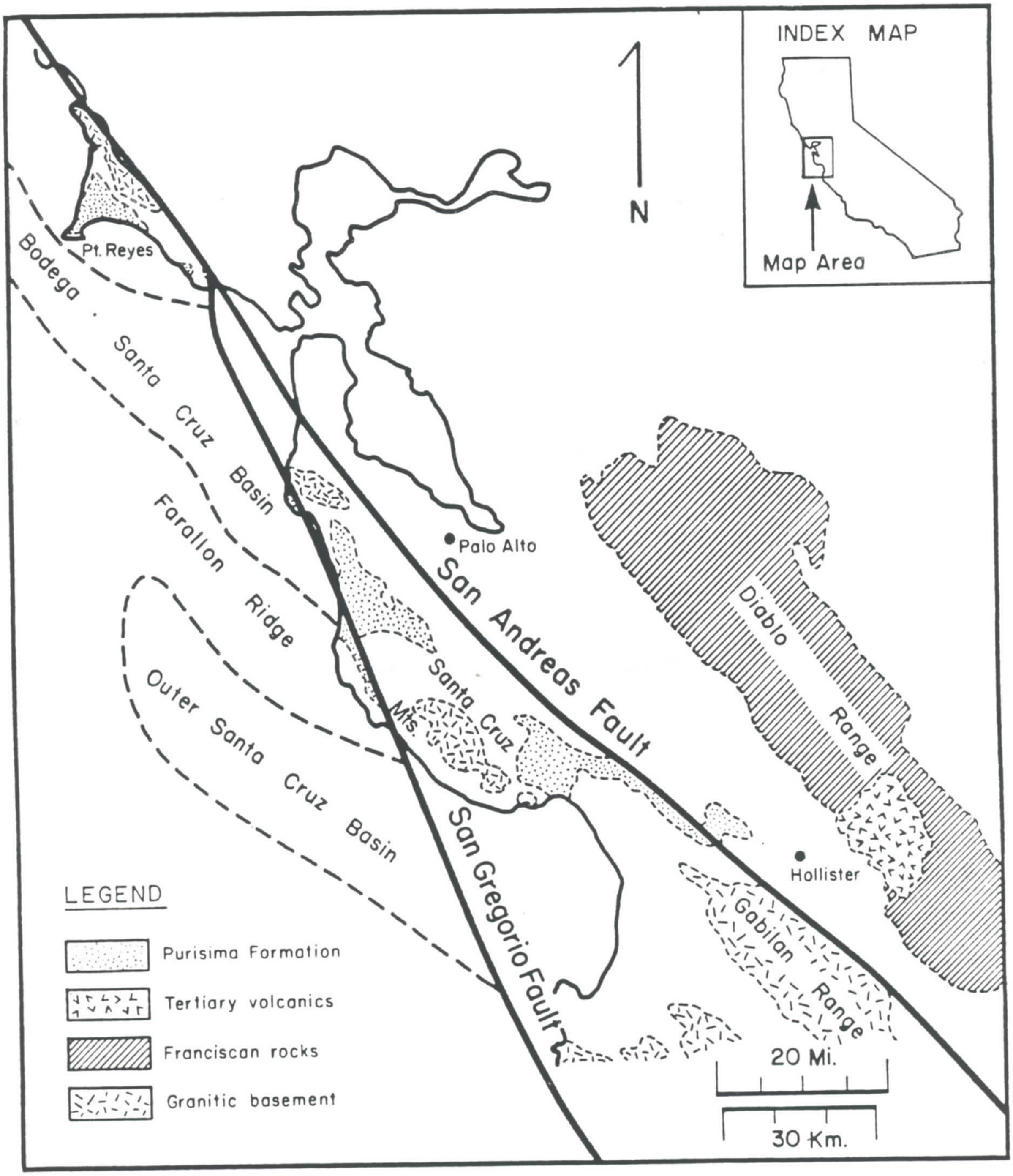


Figure 24. Tectonic setting of Neogene basins of the central California coastal margin (from Gavigan, 1984).

siltstones of the Purisima Formation. Intraformational unconformities, soft-sediment deformation structures, and alternating layers of sandstone, siltstone, and mudstone in vertical sequences throughout the Purisima indicate significant variation in depositional environments and bathymetry as a result of tectonic activity along the San Gregorio fault margin (Gavigan, 1984).

The cliffs along Drakes beach are made of light yellowish-gray diatomaceous mudstones/siltstones of the Purisima Formation with interbeds of very fine-grained quartzofeldspathic granite-derived sandstones and carbonaceous concretions up to seven feet long which occur parallel to bedding in somewhat continuous layers (Gavigan, 1984).

The onland exposure of the Purisima Formation is confined to a syncline between the Inverness Ridge to the northeast and Point Reyes on the southwest (see Figure 4). As much as 490 m (1,607 ft) of Purisima is exposed in this syncline and thins out on both flanks as a result of erosion. Offshore seismic lines show that this syncline continues to the south above granitic basement southwest of Point Reyes and may be more than 560 m (1,835 ft) of Purisima (Clark and others, 1984).

Sir Francis Drake

On December 13, 1577, Captain Francis Drake (known by the Spanish as "the Dragon") left England with five ships on a voyage of "discovery" around the world. England was competing with Spain for the New World's natural resources and England wanted to cripple Spain as a sea-going power. Drake returned three years later on September 27, 1580, with only one ship, the Golden Hinde, and 80 million dollars worth of Spanish gold and silver and a record of his travels. He was, of course, knighted for this great accomplishment.

Sailing along the Pacific coast on his one surviving ship, Drake was looking for the fabled "Northwest-Passage," but was forced to seek a safe harbor to repair his leaking ship and escape the Spanish. He was attracted by the white cliffs of Drakes Beach and its relatively quiet harbor. The cliffs reminded him of the white cliffs of Dover and he named the place Nova Albion, or New England.

It is believed that he careened his ship in the cove on the west side of Drakes Estero for 36 days in June and July of 1579. The strongest evidence for the location of this site is from an inset illustration called Portus Novane Albionis on a world map published around 1589 depicting Drake's voyage around the world by Jodocus Hondius, a Dutch cartographer.

The Drake Navigation Guild has taken much care to determine Drake's actual landing site. A comparison of the Hondius inset with a photograph of the entrance to Drakes Estero appears to substantiate this as the actual site (Aker, 1980). Further study of the site has been conducted, including historical geomorphology, archaeological trenching, and a simulation using a vessel with a similar draft as the Golden Hinde. In addition, physical evidence reported by Edward P. Von Porten from various Indian sites around the Drakes Bay consists of 77 pieces of sixteenth century Chinese porcelain apparently from Drake's cargo. All of the above findings indicate that Drake's landing place may have indeed been on the west side of Drakes Estero.

An artifact which confused the substantiation of Drake's site for years was a bronze plate found in 1936, establishing Drake's careenage near San Quentin Point. After its discovery, a local resident reported he had thrown it there during a picnic, and had originally found it at Drakes Bay. Drake had indeed left a bronze plate on a post which took possession of the land in the name of Queen Elizabeth I before he departed. However, the plate found at San Quentin Point, which was accepted for many years as real, did not pass modern metallurgical tests. It was also found to be machine rolled, not pounded, and the script did not compare to that of sixteenth century script. It was finally declared a hoax.

Treasure Hunting

Point Reyes is a dangerous area for ships with its gusty north winds and thick hanging fogs. Since Drake's time it has been the burial ground for many ships which have run aground on its treacherous shoals. Cargo from those ships has been a constant source of interest for generations of beachcombers.

The first ship to sink in Drakes Bay was the San Agustin in 1595, 16 years after Drake's visit. Captain Sebastian Rodriguez Cermeno's ship had dropped anchor and the crew was exploring inland to take on provisions. While ashore a sudden storm arose and the ship sank. Its known cargo of silks, wax, spices, and Ming Dynasty porcelain and probable cargo of gold and gems was never retrieved nor was the exact location known. Since then, 73 major wrecks have occurred, 37 of them fatal, with 20 localities unknown.

It is the San Agustin which has attracted Robert Marx, a self-proclaimed "nautical archeologist," whose specialty is salvaging galleons. According to Marx, the San Augustin sank in 30 ft of water and approximately 800 artifacts have washed ashore (Castle, 1989). Marx has obtained all local, state, and most federal permits except one from NOAA which controls the Farallon Islands-Point Reyes National Marine Sanctuary. To date he has not been successful in obtaining the permit from NOAA, but it is just a matter of time before NOAA submits to pressure from the State Lands Commission to permit this salvage operation.

Marx's agreement with the state ensures that California will monitor the operation and will get the first pick of the artifacts, right to appraise them, and 50% of all goods after the value exceeds $25,000.

CONCLUSION

If there is any time remaining on your visit to Point Reyes, be sure to stop by the Point Reyes Lighthouse. There you can examine the Point Reyes conglomerate near the parking lot and try to imagine where the clasts originated. The view from the lighthouse is spectacular and, if the time and conditions are right, you should be able to observe gray whales swimming offshore.

END OF ROAD LOG

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APPENDIX

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GEOLOGY OF POINT REYES PENINSULA AND IMPLICATIONS FOR SAN GREGORIO FAULT HISTORY

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ABSTRACT

Onland mapping and offshore seismic profiling of the Point Reyes area enable the recognition of three distinct facies within the granitic basement rocks and recognition of two Neogene lithogenetic sequences that are separated by a regional unconformity--a middle and upper Miocene sequence (Laird Sandstone and Monterey Formation) and an upper Miocene and Pliocene sequence (Santa Margarita Sandstone, Santa Cruz Mudstone, and Purisima Formation).

Comparison of similar basement and Tertiary sedimentary rocks in the Point Reyes, Santa Cruz Mountains, and Monterey areas indicates about 150 km (90 miles) of right-slip along the San Gregorio fault since late Miocene time, rather than the 70-115 km (43-70 mi) suggested previously by other geologists. This slip added to slip for the San Andreas fault produces a total displacement of about 455 km (280 miles) for the San Andreas fault north of San Francisco.

INTRODUCTION

The San Gregorio fault zone is part of the larger San Andreas fault system of California that forms the active tectonic boundary between the Pacific and North American plates. From its type area in the western Santa Cruz Mountains, the San Gregorio fault zone has been traced southward at least across Monterey Bay and northward to its juncture with the San Andreas fault near Bolinas in Marin County (Greene and others, 1973), a total distance of at least 200 km (125 miles).

Onshore mapping in the Santa Cruz Mountains by Clark (1970 and 1981) has demonstrated that the San Gregorio is a zone of deformation as much as 3 km (2 miles) wide that east of Año Nuevo Point includes at least five northwesterly-trending faults. Detailed stratigraphy and comparison of the onland geologic sections across this zone by Clark and Brabb (1978) have revealed significant differences in depositional and tectonic histories on either side of the fault that implied extensive lateral displacement.

Estimates of the magnitude of this displacement have varied. Based on his offshore study of gravity anomalies, Silver (1974) suggested 80 to 90 km (50 to 56 mile) right-lateral offset on the San Gregorio fault. Graham and Dickinson (1978), matching pairs of onland geologic features, postulated about 115 km (70 miles) of Neogene right-slip. A lesser amount of total displacement was suggested by Greene (1977), who postulated 70 km (43 miles) based on displaced submarine canyons, and by Howell and Vedder (1978), who estimated 70 km (43 miles) of slip based on their reconstruction of the Late Cretaceous paleogeography of the Salinian block.

A reconnaissance of the Point Reyes area by Clark in 1977 revealed, however, that the Tertiary sequences at Point Reyes and in the southern Santa Cruz Mountains were not as "nearly identical" as had been postulated by Graham and Dickinson (1978). Likewise, a preliminary comparison of Upper Cretaceous and Paleocene sequences of the central California coastal area raised serious questions about the validity of Howell and Vedder's (1978) paleogeographic reconstruction.

To clarify the offset history of the San Gregorio fault, we began in 1978 a study of the rock sequences of the Point Reyes Peninsula west of the San Andreas fault. Onland mapping of this area during parts of the summers of 1978 and 1979 and offshore seismic profiling aboard the R/V Sea Sounder during June 1979 have resulted in a revision of the Tertiary stratigraphy of the area. This revised geology permits more meaningful comparisons with the correlative rock sections that we had previously mapped to the south both in the Santa Cruz Mountains and in the Monterey Bay region east of the San Gregorio fault.

The purpose of this paper is to summarize the geologic section of the Point Reyes Peninsula and then, by comparing sections that we have studied on both sides of the San Gregorio fault, to reconstruct the Neogene history of this important structure.

Although the displacement that we propose must continue to the south into the Santa Lucia Range and perhaps beyond, the extension of the San Gregorio fault to the south and the offset history of related faults in that region are beyond the scope of the present study.

GEOLOGIC SECTION OF THE POINT REYES PENINSULA

The Point Reyes Peninsula is a roughly triangular land area in Marin County that projects westward from the valley of the San Andreas fault to an apex at Point Reyes. The most comprehensive publication on the geology of this area is by Galloway (1977), who admirably summarized the previous geologic work. He also defined the Point Reyes Conglomerate of Paleocene age and the Drakes Bay Formation of Pliocene age and mapped the distribution of rock units at a scale of 1:48,000. Our work represents a modification of Galloway's mapping and includes the recognition of three distinct facies within the granitic basement rocks and recognition of two lithogenetic sequences that are separated by a regional unconformity that occur within his Monterey Shale--a middle and upper Miocene sequence (Laird Sandstone and Monterey Formation) and an upper Miocene and Pliocene sequence (Santa Margarita Sandstone, Santa Cruz Mudstone, and Purisima Formation).

Pre-Tertiary crystalline rocks

Granitic rocks of the Salinian block are exposed at the Point Reyes promontory, along Inverness Ridge to the east, and at Tomales Point to the north (fig. 1). Modal analyses of these rocks are shown in figure 2.

The most distinctive granitic unit is the porphyritic granodiorite of Point Reyes. Prominent, euhedral K-feldspar phenocrysts average 2 to 3 cm (0.8 to 1.2 in) and

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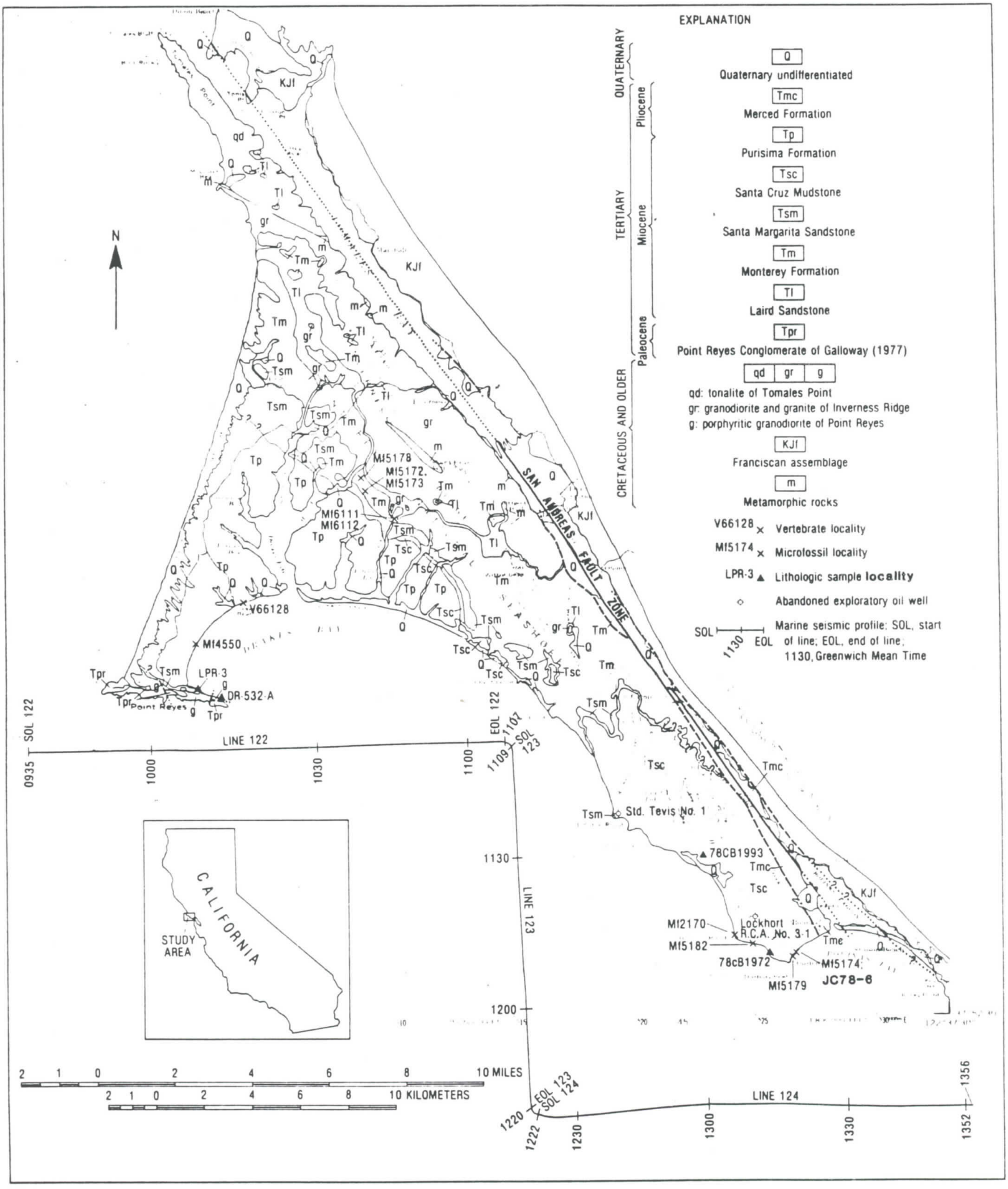

Figure 1. Generalized geologic map of the Point Reyes Peninsula showing the location of marine seismic profile lines (see figs. 3, 4, and 5), places where fossils and rocks were collected, and exploratory oil wells. Geology from Galloway (1959, 1977), extensively modified by J. C. Clark and E. E. Brabb, 1978-81.

GEOLOGY OF POINT REYES PENINSULA AND IMPLICATIONS FOR SAN GREGORIO FAULT HISTORY

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ABSTRACT

Onland mapping and offshore seismic profiling of the Point Reyes area enable the recognition of three distinct facies within the granitic basement rocks and recognition of two Neogene lithogenetic sequences that are separated by a regional unconformity--a middle and upper Miocene sequence (Laird Sandstone and Monterey Formation) and an upper Miocene and Pliocene sequence (Santa Margarita Sandstone, Santa Cruz Mudstone, and Purisima Formation).

Comparison of similar basement and Tertiary sedimentary rocks in the Point Reyes, Santa Cruz Mountains, and Monterey areas indicates about 150 km (90 miles) of right-slip along the San Gregorio fault since late Miocene time, rather than the 70-115 km (43-70 mi) suggested previously by other geologists. This slip added to slip for the San Andreas fault produces a total displacement of about 455 km (280 miles) for the San Andreas fault north of San Francisco.

INTRODUCTION

The San Gregorio fault zone is part of the larger San Andreas fault system of California that forms the active tectonic boundary between the Pacific and North American plates. From its type area in the western Santa Cruz Mountains, the San Gregorio fault zone has been traced southward at least across Monterey Bay and northward to its juncture with the San Andreas fault near Bolinas in Marin County (Greene and others, 1973), a total distance of at least 200 km (125 miles).

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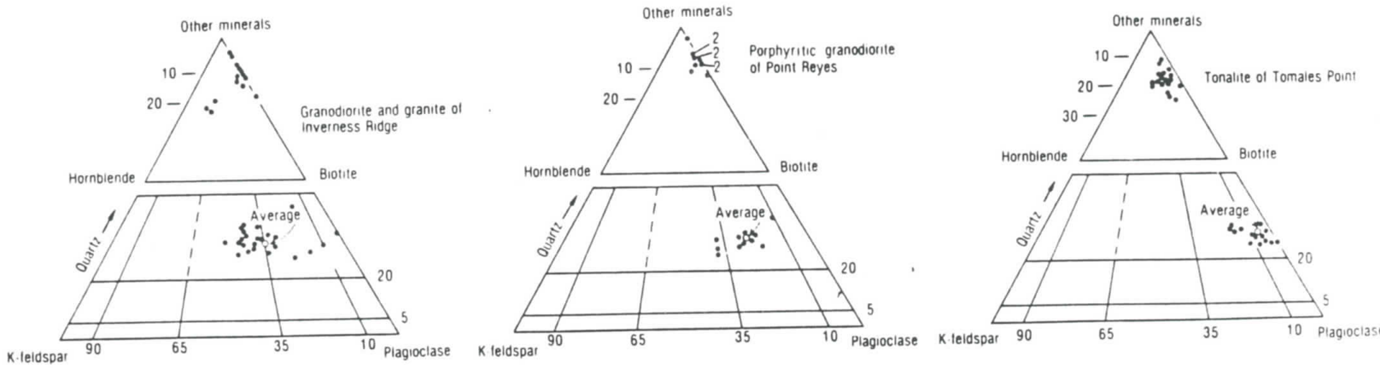

Figure 2. Modal plot of granitic rocks of the Point Reyes area.

are as long as 5 cm (2 in). Locally this rock is not porphyritic. Although onland exposures of the granodiorite are restricted to two small areas at Point Reyes, this rock probably forms the basement to the south and to the east. Seismic profiling indicates that crystalline rocks crop out on the sea floor 2 km (1.2 mi) south of Point Reyes (line 122, fig. 3). At Point Reyes, similar porphyritic granodiorite occurs as the dominant clast in conglomerate of the overlying Point Reyes Conglomerate of Galloway (1977). These granodiorite clasts that are as much as 2 to 3 m (6.6 to 10 ft) long contain conspicuous K-feldspar phenocrysts that average 3 cm (1.2 in), commonly range up to 4 or 5 cm (1.6 to 2 in), and locally are as long as 9 cm (3.6 in). The abundance of these porphyritic clasts and a postulated west to northwest paleocurrent direction for the Point Reyes Conglomerate suggest that the porphyritic granodiorite forms the basement to the east and southeast, where it is now covered by younger Tertiary rocks.

Granodiorite and granite are exposed along Inverness Ridge west of the San Andreas fault (fig. 1). These felsic rocks contain metasedimentary inclusions and roof pendants of garnet- and sillimanite-bearing schist and gneiss, quartzite, calc-hornfels, and marble (Ross, 1977, p. 375) Dikes and masses of aplite and alaskite are locally abundant.

At Tomales Point, hornblende-biotite tonalite forms the basement. The contact between this tonalite and the granodiorite and granite of Inverness Ridge is marked by a metasedimentary septum both along the coast at McClures Beach and in beach-cliff exposures across the peninsula to the southeast. The contact is not exposed between these two beach-cliff exposures.

About 10 km up the coast from the northernmost Tomales Point exposures, a similar hornblende-biotite tonalite crops out in a few square kilometer area near Bodega Head. These Bodega Head exposures are the northernmost land outcrop of granitic rocks of the Salinian block west of the San Andreas fault. Ross (1972, 1978) reports abundant dark diorite inclusions in the tonalite of Bodega Head and believes that the tonalite at Bodega Head and Tomales Point are probably parts of the same granitic mass, herein referred to as the tonalite of Tomales Point.

The onland exposures of porphyritic granodiorite of Point Reyes are 11 km (7 mi) from the nearest granitic exposures to the northeast. Dark inclusions resembling the tonalite of Tomales Point have been found in the Point Reyes mass, suggesting that the porphyritic rocks of Point Reyes may be physically connected at depth with the granitic exposures of Inverness Ridge and Tomales Point. A buried contact between the Point Reyes and Inverness Ridge masses would probably trend northwest-southeast based on present granitic outcrop distribution and is assumed to parallel the Tomales Point-Inverness Ridge mass contact.

The age of granitic rocks in the Point Reyes and Bodega Head areas has been discussed by Ross (1978, p. 518-519) who concluded from radiometric dating by others that the rocks probably crystallized about 100 m.y. ago, during the Early Cretaceous.

Tertiary sedimentary rocks

Resting nonconformably upon the crystalline basement of the Point Reyes area are as much as 4,370 m (14,330 ft) of Tertiary sedimentary rocks that comprise three sedimentary rock sequences, each of which is bounded by unconformities (fig. 6). The oldest sequence is of Paleocene age and rests depositionally upon the porphyritic granodiorite of Point Reyes. As much as 210 m (700 ft) of interbedded conglomerate and sandstone that are exposed near the lighthouse, previously mapped as Laird Sandstone by Weaver (1949), were designated by Galloway (1977) as the type section of his Point Reyes Conglomerate. He restricted the Laird to the area along Inverness Ridge and this usage is followed in this report.

At its type section, The Point Reyes Conglomerate of Galloway consists of very thick, graded arkosic sandstone beds and very thick sandy conglomerate beds, which locally have channelled into the underlying sandstone. Interbedded with these units are more thinly-bedded and finer-grained arkosic sandstone units. Conspicuous in the conglomerates are porphyritic granodiorite clasts as much as 2 to 3 m (6.7 to 10 ft) long. Clasts consist of 30 to 50 percent porphyritic granodiorite boulders, 30 to 40 percent purple and black porphyritic siliceous volcanic pebbles and cobbles, and 10 to 20 percent light-colored quartzite pebbles, with lesser amounts of red chert, black aphanitic volcanic, and green volcanic(?) pebbles. The percentage of granodiorite clasts appears to be higher lower in the section. An isolated knob 2 to 3 km (1 to 2 mi) east of the lighthouse section that presumably is stratigraphically higher is a sandy pebble-cobble conglomerate. There, the clasts are dominantly varicolored porphyritic volcanic with fewer light-colored quartzite varieties.

The conglomerate and sandstone beds consist primarily of lithofacies A and B of Ricci-Lucchi's (1975) fan facies classification. The Paleocene sequence displays thinning and fining upward cycles typical of channelized fan deposits (S. H. Clarke, Jr., oral commun., 1978). Several conglomerate channels are oriented northwest-southeast, and limited paleocurrent data suggest west- to northwest-trending flow (Clarke, oral commun., 1978).

Siltstone rip-up clasts contain large specimens of the arenaceous benthic foraminifer Bathysiphon, and a Paleocene arenaceous fauna collected by Brabb from near the base of the lighthouse section and listed by Galloway (1977, p. 19) is characteristic of bathyal depths. Thus, these

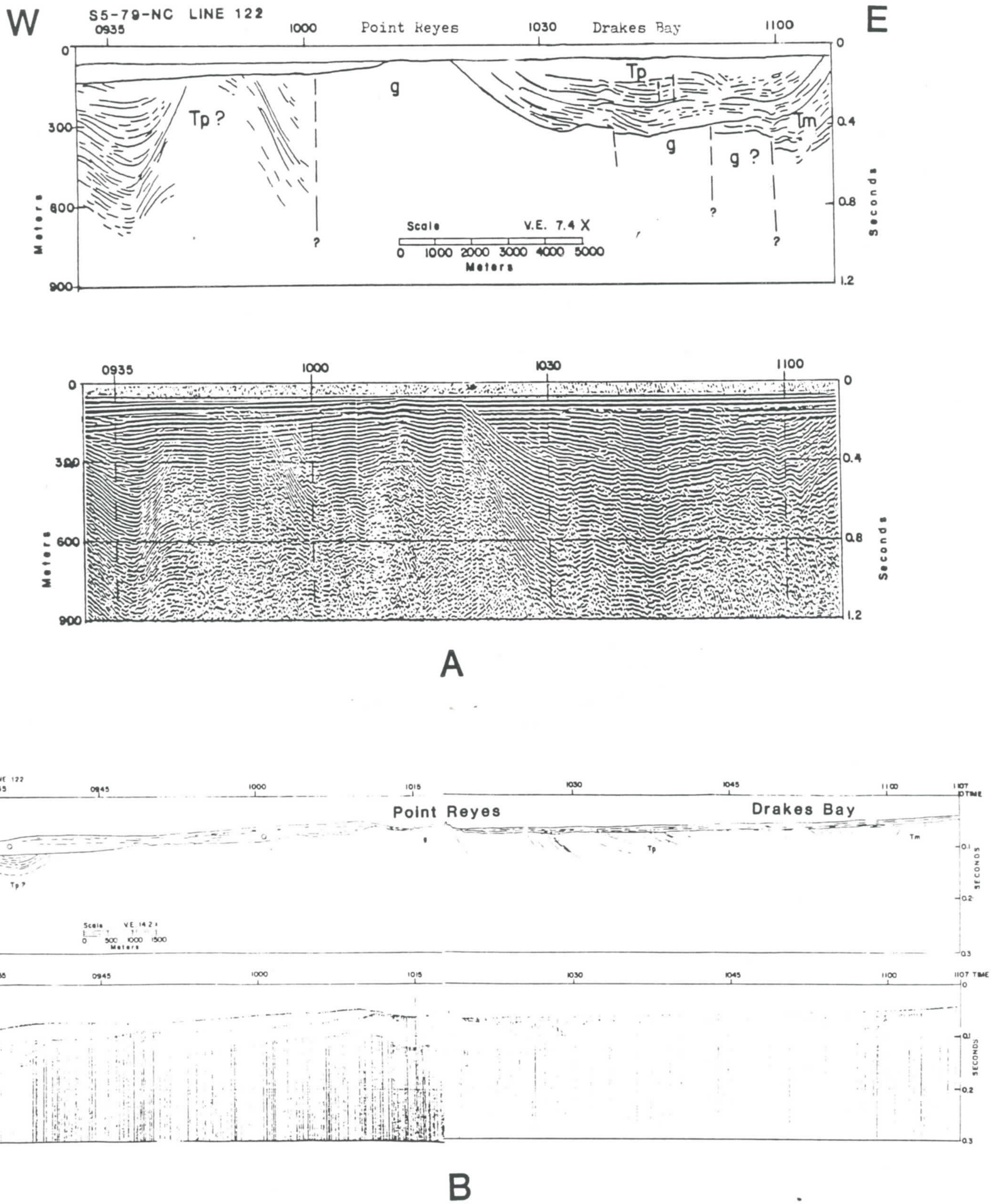

Figure 3. West to east seismic reflection profiles run offshore from Point Reyes and Drakes Bay in 1979. A, 160 kj. sparker seismic reflection profile and line drawing showing folds and faults that can be correlated with onshore geology. B, high-resolution, Uniboom, seismic reflection profile and line drawing showing relationship of Tertiary and older rocks with the overlying Quaternary cover. See Fig. 1 for explanation of symbols and location of trackline.

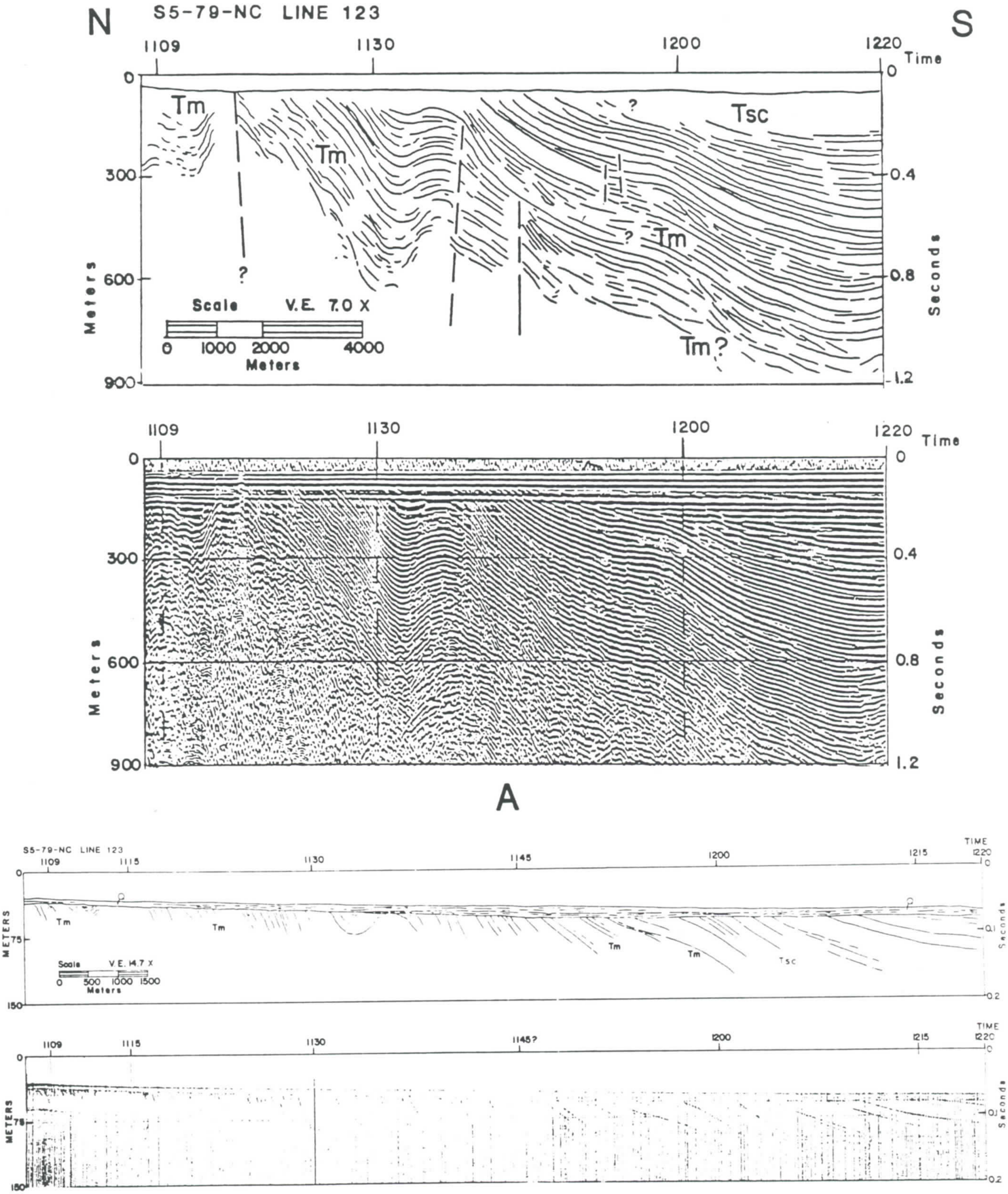

Figure 4. North to south seismic reflection profiles in the Drakes Bay area. A, 160 kj sparker seismic reflection profile and line drawing, showing folds and faults. B, high-resolution, Uniboom, seismic reflection profile, and line drawing, showing unconformity between Tertiary and Quaternary rocks and sediments. See Fig. 1 for explanation of symbols and location of trackline.

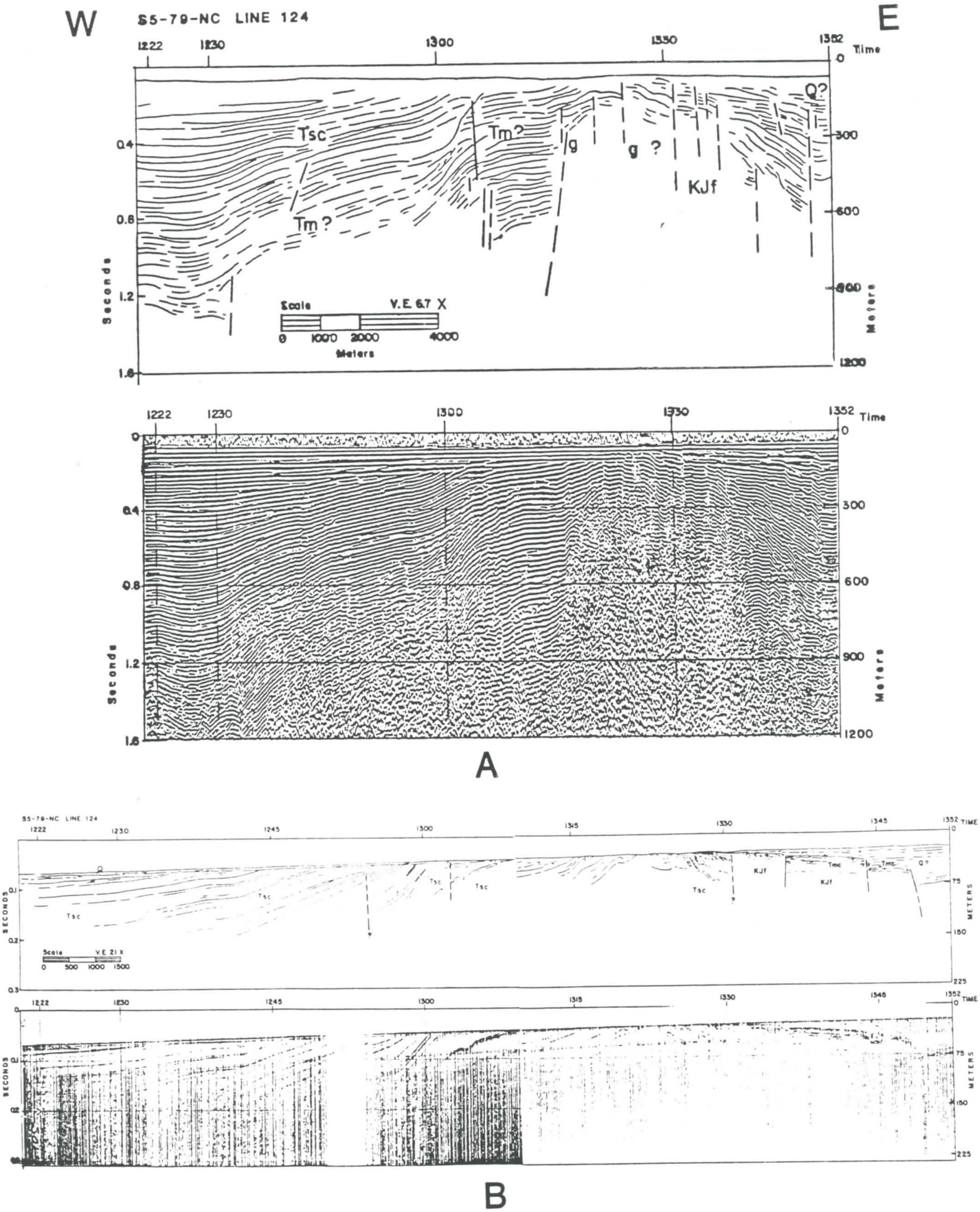

Figure 5. West to east seismic reflection profiles across the mouth of Bolinas Bay. A, 160 kj seismic reflection profile and line drawing showing faults and folds associated with the San Andreas fault zone. B, high-resolution, Uniboom, seismic reflection profile and with line drawing showing folds, faults and outcrop of Tertiary rocks. See Fig. 1 for explanation of symbols and location of trackline.

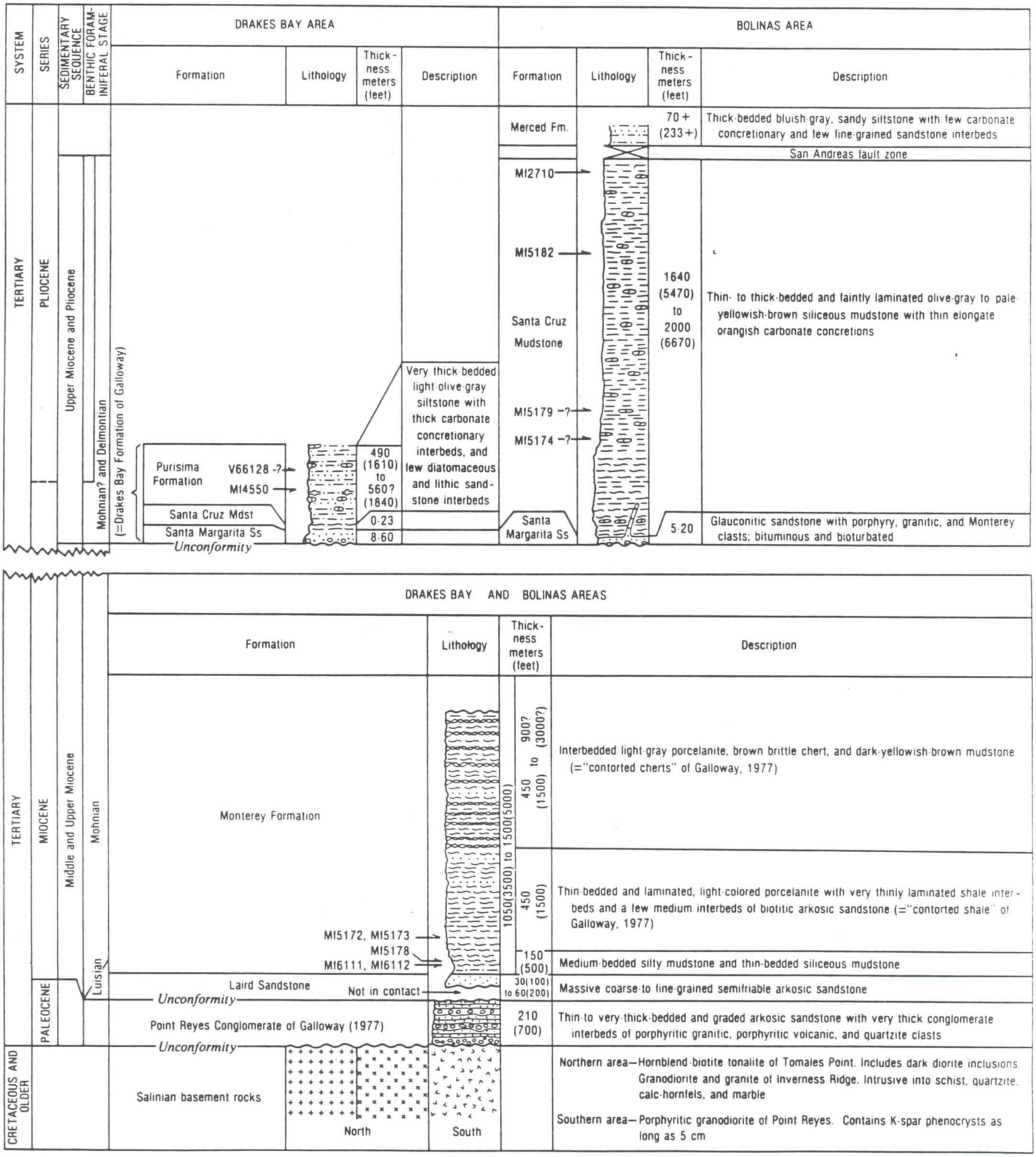

Figure 6. Composite stratigraphic column for the Point Reyes area west of the San Andreas fault.

beds were probably laid down as part of a northwesterly-trending, upper mid-fan channel complex that was derived from a porphyritic granodiorite and a silicic volcanic or older conglomerate terrain to the east and southeast.

Although surface exposures of the Paleocene sequence are restricted to the Point Reyes promontory, Paleocene rocks may be present in the subsurface to the east. The Standard Tevis No. 1 well drilled near Double Point (fig. 1) about 18 km (11 mi) southeast of Point Reyes is reported by Galloway (1977, p. 65) to have penetrated lower Eocene or Paleocene beds beneath basalt.

Middle and upper Miocene sedimentary sequence

The middle and upper Miocene sequence is as much as 1,610 m (5,300 ft) thick and consists of a transgressive basal sandstone unit, the Laird Sandstone, and an overlying porcelanite unit, the Monterey Formation of this report (fig. 6).

The Laird Sandstone crops out along a band on the southwest slope of Inverness Ridge (fig. 1), where it rests nonconformably on granodiorite and granite and is conformably overlain by the Monterey Formation. Locally the Laird is calcareous and in places slightly bituminous.

Galloway (1977, p. 21) reports that the Laird Sandstone is as much as 60 m (200 ft) thick. Mollusks are rare in the sandstone. Benthic foraminifers from lower beds of the superjacent Monterey Formation are diagnostic of Luisian (middle Miocene) age in the central part of the outcrop area and are reported by Galloway to be of Mohnian (late Miocene) age to the northwest. Thus, this transgressive sandstone unit is considered to range from Luisian to Mohnian age.

The Monterey Formation of this report excludes those parts of the Monterey Shale as mapped by Weaver (1949) above the regional unconformity and the south part of the Monterey Shale as mapped by Galloway (1977). The Monterey Formation is thus restricted to the siliceous mudstone, porcelanite, chert, and shale beds that are conformable above the Laird Sandstone of this report. This formation is exposed onland in a broad band in the central part of the area that narrows to the northwest (fig.1). To the west and south, this unit is unconformably overlain by glauconitic sandstone beds of the upper Miocene and Pliocene sequence; to the east, it is truncated by the San Andreas fault.

Because of limited outcrops and complex structure, a complete Monterey section is nowhere exposed. This formation locally consists of three lithologic units (fig. 6). The lowest unit includes as much as 150 m (500 ft) of medium-bedded silty mudstone to thin-bedded siliceous mudstone that crops out west of Inverness Ridge. A southwesterly-dipping, thin-bedded porcelanite and shale unit overlies the mudstone unit on the southwest slope of Inverness Ridge, where it may be as thick as 450 m (1,500 ft). To the south, porcelanite and concretionary chert beds form the upper unit of the Monterey. The thickness of this

Table 1. Checklist of benthic foraminifers from the Monterey Formation, Point Reyes area. Samples Mf6111 and 6112 identified by Kristin McDougall, 1981. Other samples identified by A. D. Warren, 1978. See fig. 1 for the map location of the samples.

Taxon	Sample Mf 5172	Mf 5173	Mf 5178	Mf 6111	Mf 6112
Baggina californica Cushman					x
Bolivina advena striatella Cushman				x	x
B. bramlettei Kleinpell		x			
B. seminuda Cushman var.		x	cf.		
B. sinuata alisoensis Cushman and Adams			x		
B. tumida Cushman				x	
Bulimina montereyana delmonteensis Kleinpell		x			
B. ovula d'Orbigny			x		
B. spp.	x				
Buliminella curta Cushman			x		
B. subfusiformis Cushman				x	x
Epistominella subperuviana (Cushman)					x
Florilus costiferus (Cushman)					x
Fursenkoina californiensis (Cushman)		cf.	x	x	x
F. californiensis ticensis (Cushman and Kleinpell)		cf.	x		
F. subplana Barbat and Johnson		cf.			
F. sp.	x				
Globigerina spp.	x				
Globobulimina sp.		x	x		
G. pedroana (Kleinpell)			x		
Gyroidina multicamerata (Kleinpell)	x	x			
Marginulina beali (Cushman)					x
Nodosaria tympaniplectriformis Swager	x				
Pullenia miocenica globula Kleinpell					x
Uvigerina hannai Kleinpell		x			
U. modeloensis Cushman and Kleinpell			x		
U. sp.					x
Valvulineria alicia Pierce	x				
V. californica Cushman				x	x
V. grandis Cushman and Galliher	x	cf.			
V. miocenica Cushman				x	x
V. spp.	x				

upper unit is difficult to estimate because of contorted and complex folding, but it is probably more than 450 m (1,500 ft) and may be as much as 900 m (3,000 ft). Thus, the total thickness of the exposed Monterey Formation is probably on the order of 1050 to 1500 m (3,500 to 5,000 ft).

To the south on the Point Reyes Peninsula, the Monterey Formation of this report is not exposed and is covered unconformably by beds of the upper Miocene and Pliocene sequence (fig.1; and line 123, fig. 4). The Lockhart R.C.A. well near Bolinas (fig. 1) penetrated almost 1,500 m (5,000 ft) of siliceous Monterey beneath sandstone, but did not reach the base of this formation (Galloway, 1977, p. 65; R. C. Blaisdell, oral commun., 1978).

The Monterey Formation yields benthic foraminifers diagnostic of a Luisian and Mohnian (middle and late Miocene) age. Although Galloway (1977, p. 21) reports that the Monterey of the Point Reyes Peninsula is as old as Relizian, no foraminiferal faunas diagnostic of Relizian age have been recorded by Galloway or others from this area. Indeed, the oldest Miocene fauna listed by Galloway (1977, p. 25) includes Valvulineria miocenica and is diagnostic of Luisian age. Likewise, the oldest foraminiferal faunas that we collected from the lower unit of the Monterey (Mf 6111 and Mf 6112, table 1) yielded Florilus costiferus, Valvulineria miocenica, and V. californica, which are diagnostic of the Valvulineria californica Zone of the Luisian Stage. A fauna (Mf 5178, table 1) from about 60 m (200 ft) stratigraphically above the base of the Monterey is diagnostic of a Mohnian, probably early Mohnian, age, whereas faunas Mf 5172 and Mf 5173 (table 1) from about 180 m (600 ft) stratigraphically above its base are diagnostic of a Mohnian, probably a late Mohnian, age, according to A. D. Warren (written commun., 1978). Thus, as much as 60 m (200 ft) of the Monterey section locally may be assigned to the Luisian, whereas most of this formation is Mohnian (upper Miocene).

On the southwest slope of Inverness Ridge (Mf 6111 and Mf 6112, fig. 1), beds of Luisian age are nonconformable on the granitic basement. Elsewhere, to the north and to the east the lowermost beds of the Monterey that we sampled are of Mohnian age, as previously reported by Galloway (1977). Thus, the middle and upper Miocene sequence appears to transgress the crystalline basement to the north and to the east. To the south in the Standard Tevis No. 1 well near Double Point (fig. 1), beds of the middle and upper Miocene sequence probably rest unconformably on basalt that was penetrated at a depth of 1500 m (5,000 ft) (Galloway, 1977, p. 65; R.C. Blaisdell, oral commun., 1978).

Upper Miocene and Pliocene sedimentary sequence

Resting unconformably on all older rocks of the Point Reyes Peninsula are the widely transgressive beds of the upper Miocene and Pliocene sedimentary sequence. This sequence, which is as much as 2,550 m (8,500 ft) thick, consists of a basal glauconitic sandstone unit, here mapped as the Santa Margarita Sandstone, a siliceous mudstone unit, here mapped as the Santa Cruz Mudstone, and an upper siltstone, mudstone, and sandstone unit, here mapped as the Purisima Formation. Galloway (1977) mapped the basal glauconitic sandstone unit and siliceous mudstone unit as parts of his Drakes Bay Formation and of his Monterey Shale, and the upper siltstone, mudstone, and sandstone unit as part of his Drakes Bay Formation.

We have applied the formation names from the Santa Cruz Mountains to the correlative units of this sequence at Point Reyes because of the very similar stratigraphic relationships, lithologies, and fossils, as discussed later in this report. The Santa Cruz Mudstone and the Purisima Formation of the Santa Cruz Mountains had been correlated previously with strata in the Point Reyes area by Clark (1981, p. 33-34).

Santa Margarita Sandstone--The Santa Margarita Sandstone consists of distinctive glauconitic sandstone beds that rest unconformably on the highly contorted and folded porcelanite and chert beds of the Monterey Formation in south-central coastal exposures of the Point Reyes Peninsula. There, this sandstone is a greenish lithic arkose that contains 37 to 42 percent glauconite. As exposed on the beach east of Drakes Bay, the Santa Margarita includes a one-meter thick basal conglomerate with abundant Monterey chert clasts, common greenish and black porphyritic siliceous volcanic clasts, and few granitic pebbles. In seacliff exposures near Double Point, this sandstone is highly bioturbated and bituminous. In this coastal area, its thickness varies from 5 m (16 ft) to more than 20 m (65 ft).

The Santa Margarita Sandstone is conformably overlain by mudstone beds that are sandy and glauconitic above the contact and grade upward into siliceous mudstone, mapped as Santa Cruz Mudstone in this report.

The Lockhart R.C.A. No. 3-1 well near Bolinas is reported (R. C. Blaisdell, oral commun., 1978) to have penetrated at a depth of 1029 m (3,375 ft) about 20 m (65 ft) of sandstone beneath mudstone and above siliceous Monterey Formation. We believe that this sandstone is the subsurface continuation to the south of the Santa Margarita.

At the base of the Drakes Bay synclinal section, Galloway (1977) mapped a "basal glauconitic greensand" as a lower unit of his Drakes Bay Formation. There, this sandstone is from 8 to 60 m (25 to 200 ft) thick, but is not everywhere glauconitic. South of Laguna Ranch, this unit includes at its base as much as 50 m of "clean" arkosic sandstone and several thin interbeds of slightly siliceous mudstone, which in turn are overlain by several medium to thick, slightly bituminous glauconitic sandstone beds that form strike exposures.

We believe that this basal unit at Drakes Bay is a northward continuation of the Santa Margarita Sandstone that is exposed along the coast to the south for the following reasons:

(1) Glauconitic sandstone can be mapped northwestward from the coastal exposures north of Double Point through discontinuous hillside exposures to the broad synclinal Drakes Bay section (fig. 1);
(2) the terrigenous mineral composition of glauconitic sandstones from the south-central coastal section near Double Point is almost identical to that of the basal glauconitic sandstones to the north in the Drakes Bay section;
(3) in both areas, the glauconitc sandstone is unconformable upon the more strongly deformed Monterey Formation and is overlain by similar siliceous mudstone, which thins to the northwest (fig. 6).

No fossils were found in the Santa Margarita Sandstone. Based on stratigraphic relations to under- and overling formations, we believe the Santa Margarita is late Miocene.

Santa Cruz Mudstone--Siliceous mudstone beds that are conformable above the glauconitic sandstone are here assigned to the Santa Cruz Mudstone, the type section of which is near the city of Santa Cruz 120 to 140 km (75 to 87 mi) to the south.

On the Point Reyes Peninsula, the Santa Cruz

Mudstone is discontinuously exposed and extensively landslid in the central coastal area near Double Point, where it was included in both the Monterey and Drakes Bay Formations by Galloway (1977). The Santa Cruz Mudstone is more extensively developed to the southeast near Bolinas. Although Galloway (1977, p. 22) noted the lithologic similarity of the "shales" of the landslide area to those near Bolinas to the southeast, he mapped these latter beds as Monterey.

In the seacliffs north of Double Point, the lower part of the Santa Cruz Mudstone is well exposed. There, 13 m (43 ft) of thin-bedded porcelanite that resembles the Monterey is conformable above 20 m (65 ft) of bituminous glauconitic sandstone and is cut by thin bituminous sandstone dikes. The porcelanite beds grade upward into thicker and less siliceous mudstone beds with large spheroidal carbonate concretions that form discontinuous interbeds.

More than 1000 m (3,280 ft) of the Santa Cruz Mudstone are well exposed in the seacliffs near Bolinas from Duxbury Point on the southeast to Bolinas Point on the northwest. There, this formation is faintly laminated and thick bedded, olive-gray siliceous mudstone. In wave-cut exposures, bedding is defined by thin elongate orangish carbonate concretions. Along ridges to the north, thick bedding is more apparent, and the mudstone weathers mechanically into pale-yellowish-brown angular chips and blocks.

In the seacliffs southeast of Double Point, a few thin bituminous sandstone interbeds are exposed, whereas farther southeast bituminous sandstone dikes are locally common in the lower part of the mudstone section.

Chemical analyses of the Santa Cruz Mudstone from this southern part of the area are listed in table 2. Silica content increases from 66.4 percent lower in this section to 79.0 percent along ridges to the north.

Table 2. Chemical analyses of rock samples from the Santa Cruz Mudstone in the Point Reyes area. Rapid rock analyses by H. J. Rose, Jr., Project leader, and P. Hearn and S. Wargo, analysts, 1979, using methods described in U. S. Geological Survey Bulletin 1401.

		W-202235 JC 78-6	W-202229 78CB1972	W-202234 78CB1993
SiO_2	%	66.4	74.5	79.0
Al_2O_3	%	11.9	8.0	8.7
Fe_2O_3	%	4.85	3.92	1.20
MgO	%	2.3	1.8	0.7
CaO	%	1.51	1.05	0.18
Na_2O	%	1.8	2.0	0.6
K_2O	%	1.89	1.26	1.34
TiO_2	%	0.56	0.40	0.44
P_2O_5	%	0.14	0.16	0.06
MnO	%	0.03	0.04	0.01

As much as 1040 m (3,410 ft) of Santa Cruz Mudstone is exposed in the southwesterly dipping seacliff section between Duxbury and Bolinas Points. This section continues downward to the east of Duxbury Point, where it is extensively landslid, but may include as much as 600 m (2,000 ft) of additional section. Northwest of Duxbury Point, the Lockhart R.C.A. No. 3-1 well is reported to have penetrated 1029 m (3,375 ft) of gently dipping mudstone before reaching sandstone. As this well is approximately on strike with the lower part of the coherent Duxbury Point section, the Santa Cruz Mudstone in this area may be as thick as 2000 m (6,560 ft). But throughout the southern part of the Point Reyes Peninsula, the upper part of this formation has been removed by erosion.

The Santa Cruz Mudstone thins rapidly to the northwest. East of Drakes Bay and 18 km (11 mi) northwest of the Duxbury Point section, only 23 m (75 ft) of this mudstone occurs between glauconitic sandstone of the Santa Margarita Sandstone below and the siltstone beds of the Purisima Formation above. About 4 km (2 mi) farther northwest, the Santa Cruz Mudstone appears to pinch out.

The Santa Cruz is locally bioturbated and contains a diverse mega- and microfauna, but stratigraphically diagnostic fossils are rare and have been collected only from the Duxbury Point-Bolinas Point section.

Fish fragments are scattered throughout the mudstone. Fragments of the echinoids Brisaster? and Scutellaster? were reported by Galloway (1977, p. 26) from near Duxbury Point, where we found a few calcareous echinoid plates and, near Bolinas Point, a few small echinoid spines. Mollusks are extremely rare; we collected a single pelecypod specimen (Tellina?) from east of Bolinas Point.

Arenaceous benthic foraminifers are more common than calcareous varieties. Three stratigraphically diagnostic faunas from the Duxbury Point-Bolinas Point section that were identified by A. D. Warren (written commun., 1978) are listed in table 3. Warren believes that the faunas from Mf 5174 and Mf 5179 are diagnostic of early Delmontian[1/] (late Miocene) age, and that the fauna from Mf 5182 is probably also early Delmontian. The latter fauna includes Bolivina obliqua, which according to Kleinpell's (1980, p. 50) revised Miocene stratigraphy, makes its first appearance in the upper Delmontian.

Table 3. Checklist of foraminifers from the Santa Cruz Mudstone in the Point Reyes area. Samples identified by A. D. Warren, 1978. See fig. 1 for the map location of the samples.

Taxon sample	Mf 5174	Mf 5179	Mf 5182
Angulogerina sp.	x		
Bathysiphon sp.			x
Bolivina advena Cushman var.	x	x	
B. obliqua Barbat and Johnson			x
B. rankini Kleinpell	x	x	
B. seminuda Cushman		x	cf.
Buliminella curta Cushman	x	x	
Cassidulina laevigata d'Orbigny var.		x	
Fursenkoina californiensis (Cushman)		x	
Globobulimina pacifica Cushman	x		
Rotalia garveyensis Natland		x	
Uvigerina senticosa Cushman	cf.	x	
Virgulina subplana Barbat and Johnson	x		

1/ Pierce (1972) and Barron (1976) believe that the Delmontian is partly coeval with the Mohnian Stage.

Radiolarians are locally rare to common and usually pyritized. Diatoms occur throughout the mudstone and are generally preserved as molds. A single stratigraphically diagnostic flora from near Bolinas Point (Mf 2710) that was identified by John A. Barron (written commun., 1975) included the following taxa:

Diatoms:
- Actinocyclus ehrenbergii var. tenella (Brebisson) Hustedt
- A. ingens Rattray (v. rare, fragmented)
- Actinoptychus undulatus f. maxima Schmidt
- Coscinodiscus nodulifer Schmidt
- Denticula hustedtii Simonsen and Kanaya (v. rare, fragmented)
- Lithodesmium minusculum Grunow
- Rouxia californica Peragallo (rare)
- Thalassiosira cf. T. decipiens (Grunow) Joergensen
- T. nativa Sheshukova-Poretzkaya (rare)
- T. antiqua (Grunow) Cleve-Euler (common)

Silicoflagellate:
- Distephanus speculum v. A (few)

Barron (oral commun., 1980) now assigns this assemblage to Subzone a of North Pacific Diatom Zone X, which he believes is of late late Miocene age.

Stratigraphically diagnostic fossils were not recovered from the Santa Cruz Mustone at Double Point or to the north, east of Drakes Bay. Galloway (1977, p. 25) states:

"Deposition of Monterey-type shales seems to have continued for a short period after the glauconitic sand at the base of 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."

As a diatom flora (Mf 4550) that we collected from the Purisima Formation from approximately 240 m (800 ft) stratigraphicaly above the basal glauconitic sandstone is believed by Barron (oral commun., 1980) to be diagnostic of Subzone b of North Pacific Diatom Zone X (latest Miocene), the Santa Cruz Mudstone that overlies the glauconitic sandstone east of Drakes Bay may be contemporaneous with the upper part of the Santa Cruz Mudstone section to the south near Bolinas.

On the Point Reyes Peninsula, the Santa Cruz Mudstone is of late Miocene age and thus is correlative with the type Santa Cruz Mudstone of the Santa Cruz Mountains to the south.

Purisima Formation--Galloway (1977) assigned the beds that form the white cliffs of Drakes Bay to his Drakes Bay Formation and designated the seacliff section that extends northeastward from Point Reyes to Drakes Estero as the type section. In mapping, he subdivided his formation into two units: a relatively thin, basal glauconitic sandstone unit overlain by a thicker, interbedded siltstone and mudstone unit.

In describing the stratigraphic relations within his Drakes Bay Formation, Galloway (1977, p. 28) states:

"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."

As previously discussed, we believe that the "shale immediately overlying the greensand" is a northward continuation of that exposed at Duxbury Point and have differentiated these beds as Santa Cruz Mudstone. We have assigned the siltstone beds at Drakes Bay that are locally conformable upon the Santa Cruz Mudstone to the Purisima Formation based on the lithologic and paleontologic similarity of these beds to the Purisima Formation of the Santa Cruz Mountains to the south.

The Purisima Formation at Drakes Bay is typically thick to very thick bedded, light-olive-gray siltstone that upon weathering becomes nodular and yellowish gray. Locally the siltstone is diatomaceous and includes a few dark, irregular replacement chert pods. Spheroidal carbonate concretions are elongate as much as 2 m (7 ft) parallel to the bedding and form discontinuous interbeds. Several thick interbeds of light-olive-gray fine-grained sandstone are semifriable and commonly bioturbated. The sandstone is a lithic arkose with common silicic volcanic and few andesitic rock fragments and a distinctive heavy mineral suite of green, brown, and basaltic hornblende, hypersthene, and augite.

Onland exposures of the Purisima are confined to a broad syncline between Inverness Ridge on the northeast and Point Reyes on the southwest (fig. 1). There, this formation is as much as 490 m (1,607 ft) thick.

Offshore seismic profiling (line 122, fig 3a) reveals that this synclinal section continues to the south above the granitic basement. To the west and south of the Point Reyes promontory, an acoustically similar section that is most probably the Purisima is folded along a syncline and anticline and appears to be faulted against the granite to the east. There, more than 560 m (1,835 ft) of section are preserved in the syncline. Throughout the Drakes Bay area, the top of the Purisima Formation has been removed by erosion.

A diverse fossil fauna and flora has been collected from the Purisima in the Point Reyes area. Galloway (1977, p. 31-34) listed fossils from his Drakes Bay Formation that had both a Miocene and Pliocene aspect. Based largely on a potassium-argon date of 9.3± 0.5 m.y. on glauconite from the basal sandstone, he assigned the Drakes Bay to the Pliocene. As the Miocene-Pliocene boundary more recently has been placed at 5 m.y. (Berggren, 1972), this glauconite date suggests that at least part of this Purisima is Miocene in terms of the European standards. Repenning and Tedford (1977, p. 25), however, have questioned the validity of this glauconite date.

A siltstone sample (Mf 4550) that we collected in the seacliff section at Drakes Bay from approximately 240 m (800 ft) above the base of the Purisima yielded the following stratigraphically diagnostic diatoms, identified by John A. Barron (written commun., 1977):

- Denticula kamtschatica Sabelina
- Nitzschia rolandii Schrader (young form)
- Thalassiosira antiqua (Grunow) Cleve-Euler
- T. hyalinopsis Barron
- T. lineata Jouse
- T. nativa (of Schrader, 1973)

Barron correlates this flora with Subzone b of North Pacific Diatom Zone X. Although he had earlier assigned this flora to the earliest Pliocene, based on recent refinements in diatom biostratigraphy, Barron (written commun., 1980) now considers this flora to be latest Miocene.

Repenning and Tedford (1977, p. 81) suggest that the pinniped fauna from the Drakes Bay Formation of Galloway (1977) at Point Reyes, Purisima Formation of this report, is diagnostic of a late late Miocene or Pliocene age, "possibly no older than 6 m.y. and possibly as young a 4 m.y." A diagnostic element of this fauna is a primitive fur seal Thalassolen macnallyae, which they (1977, p. 67) record as from the basal glauconite bed. Their description of the type locality (UCMP locality V66128), however, places this specimen not in the basal glauconite bed but rather well up in the siltstone section and stratigraphically above the level from which we collected the latest Miocene diatom flora.

The only other reported occurrences of T. macnallyae are from the Purisima Formation of the Santa Cruz Mountains, where referred specimens have been collected from both the uppermost Miocene and Pliocene parts of the section (Repenning and Tedford, 1977, p. 67-69).

In terms of present-day European standards, as much as 240 m (800 ft) of the Purisima Formation at Drakes Bay falls within the late Miocene, whereas the upper part that is not as well dated is considered to range into the early Pliocene.

Merced Formation--On the Point Reyes Peninsula the Merced Formation is confined to the San Andreas fault zone near Bolinas and is not seen in depositional contact with any of the rocks to the west. In the seacliff at Bolinas, it is thick bedded, blue-gray sandy siltstone with a few thin carbonate concretionary inferbeds and a few cross-bedded fine-grained sandstone interbeds. The fossil fauna listed by Galloway (1977, table 6) is diagnostic of Pliocene age.

CORRELATIONS ACROSS THE SAN GREGORIO FAULT

Correlation of the Neogene sequences of the Santa Cruz Mountains with those of the Point Reyes Peninsula was suggested by Clark (1966), and emphasized by Graham and Dickinson (1978) in their discussion of apparent offsets across the San Gregorio fault. Noting also similarities in the Salinian basement and in the Paleocene rocks of both areas, these latter workers suggested a minimum of 115 km (72 mi) and a probable 120 km (75 mi) of offset of the Point Reyes--Santa Cruz Mountains (Ben Lomond Mountain) sections.

A major problem of this suggested correlation, however, is the absence in the Santa Cruz Mountains of a comparable thick, porcelaneous and cherty Mohnian section. Our mapping of the Point Reyes Peninsula has revealed that the porphyritic granodiorite, together with the Paleocene rocks and the middle to upper Miocene sedimentary sequence of that area, is more probably correlative with the rocks of the Monterey Peninsula to the south, whereas the upper Miocene to Pliocene sedimentary sequence is remarkably similar to the contemporaneous section of the Santa Cruz Mountains. These correlations thus suggest a total right-slip along the San Gregorio fault of as much as 150 km (94 mi) that began in late Mohnian (late Miocene) time with progressively less offset of younger units.

Salinian basement rocks

The most distinctive basement rock of the Point Reyes Peninsula is the porphyritic granodiorite of Point Reyes that also occurs as abundant clasts in the overlying Point Reyes Conglomerate of Galloway (1977). This granitic rock is strikingly similar to the porphyritic granodiorite of Monterey, which Ross (1978, p. 514) states "is probably the most distinctive granitic unit in the central Salinian block." Modal analyses are shown in figure 7. Both have prominent euhedral K-feldspar phenocrysts, although in both areas these rocks are not everywhere porphyritic. The phenocrysts do not exceed 5 cm (2 in) in the basement

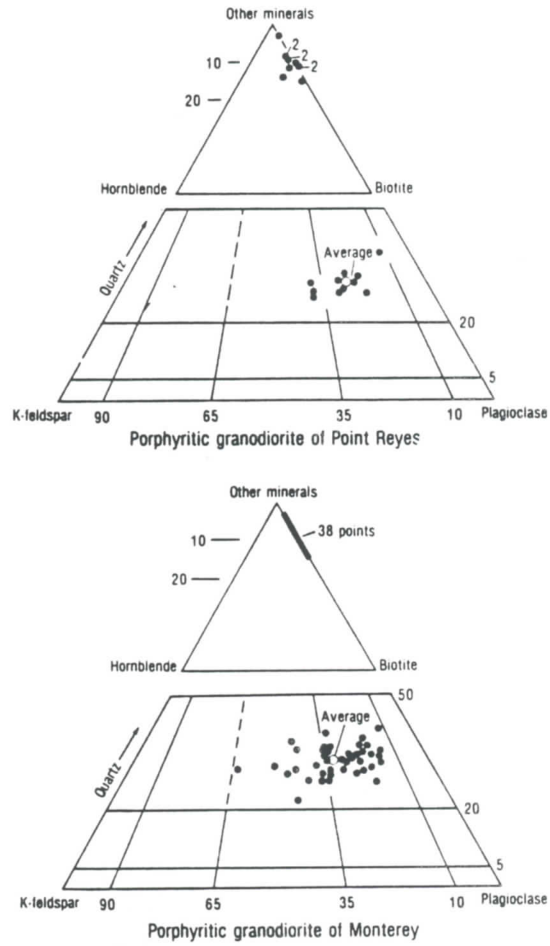

Figure 7. Modal plots of the porphyritic granodiorites of Point Reyes and Monterey.

exposures at Point Reyes but are as long as 9 cm (3.6 in) in boulders of the overlying Paleocene conglomerate, whereas Monterey phenocrysts are locally as long as 15 cm (6 in).

The extreme development of coarse phenocrysts, however, is local in the Monterey mass--commonly the phenocryst size in both masses is similar. The modal mineralogy of the two masses is likewise similar--the variations are well within the limits of normal plutonic units. One possibly significant difference between the two masses is that the specimens of the Point Reyes mass contain about 1 percent hornblende, whereas hornblende was not observed in the Monterey mass. Also the Monterey mass has primary muscovite, which is missing in the Point Reyes mass. The granodiorite of Cachagua, on the other hand, which appears to be in gradational contact with the Monterey mass, does contain hornblende, as does a suspected correlative of the Monterey mass in the La Panza Range. Thus the overall physical appearance and modal mineralogy suggest that these two masses are compatible and potential correlatives.

Chemical analyses for the Point Reyes and Monterey rocks are given in table 4 and are similar. The similar chemical character of these two masses is further accentuated by the ternary plots Q-Or-(Ab + An), Or-Ab-An, and Alk-F-M. Of possible significance is the fact that both masses have normative corundum; 1.4 percent for Point Reyes, and about 3.0 percent for Monterey. The 34 percent average of normative quartz is higher, however, in the Monterey mass than in the Point Reyes mass, but some

Table 4. Chemical analyses of the porphyritic granodiorites of Point Reyes and Monterey. Data sources: DR-532A, Mo-1B (Ross, 1972); DR-1973, 1974, Mop-1 (Ross, 1977); LPR-3 (J. C. Clark).

	Pt. Reyes			Monterey				
	DR-532A	LPR-3	Avg	Mo-1B	DR-1973	DR-1974	Mop-1	Avg.
SiO_2	70.2	71.02	70.6	73.5	69.2	72.3	73.2	72.1
Al_2O_3	15.4	15.00	15.2	14.2	16.5	15.6	15.3	15.5
Fe_2O_3	.74	2.80	2.6	.53	1.2	.80	1.9	1.1
FeO	1.6			.83	1.7	1.0	.08	.9
MgO	.97	0.75	.9	.33	.56	.42	.45	.4
CaO	3.0	2.50	2.8	2.1	2.6	2.2	2.1	2.3
Na_2O	3.3	3.27	3.3	3.7	3.8	3.3	2.4	3.3
K_2O	3.2	3.63	3.4	3.3	2.8	3.1	3.1	3.1
H_2O^-	.09	-	-	.09	.24	.24	.39	.2
H_2O^+	.64	-	-	.68	.67	.50	.34	.6
TiO_2	.59	0.43	.5	.20	.43	.26	.23	.3
P_2O_5	.14	0.10	.1	.05	.10	.06	.06	.1
MnO	.11	0.043	.1	.08	.06	.06	.06	.1
CO_2	$<.05$	-	-	$<.05$	-	-	-	-
TOTAL	99.98	99.54	99.5	99.79	99.86	99.84	99.71	100.0

Monterey samples are comparable to the Point Reyes value.

Inferred contacts between the porphyritic granodiorite of Point Reyes, the granodiorite and granite of Inverness Ridge, and the tonalite of Tomales Point are shown on figure 8, upon which limits also have been placed on the Monterey granodiorite and Vergeles--Ben Lomond tonalite masses. The restoration of 150 km (94 mi) of right-slip along the San Gregorio fault shows a remarkably close fit of these similar granitic masses (fig. 9).

This restoration juxtaposes the Tomales and Ben Lomond masses. Both of these granitic bodies are predominantly hornblende-biotite tonalite and significantly both contain abundant dark dioritic inclusions, which Ross (1972, p. 7) notes "are somewhat atypical of central Coast Range granitic rocks."

Although the intermediate Inverness mass is juxtaposed with a thick sedimentary section, there are some felsic rocks in the Gabilan Range just south of the Vergeles mass that make a gross match. Additionally, the Texaco-Davies well east of Monterey Bay (fig. 8) is reported (Ross and Brabb, 1973, p. 278) to have penetrated granodiorite beneath the Tertiary cover.

Initial strontium isotopic compositions ($Sr^{87}/Sr^{86} = r_i$) of Mesozoic granitic rocks in central California were found by Kistler and Peterman (1973) to show a systematic areal variation that was independent of age. In testing suggested offsets of basement rocks, Kistler, Peterman, Ross, and Gottfried (1973) determined the r_i of Mesozoic granitic rocks in the vicinity of the San Andreas fault zone from the Gualala area in the north to the southern California batholith. Within the Salinian block, they found r_i values north of Monterey Bay to be lower than those to the south. The Ben Lomond, Montara, Tomales, and Bodega masses had r_i values of less than 0.7068, whereas the Monterey mass had an r_i of 0.7082.

Kistler (written commun., 1980) determined the r_i of a porphyritic granodiorite sample (LPR-3, fig. 1) from Point Reyes to be 0.7077. This r_i value is anomalously high for

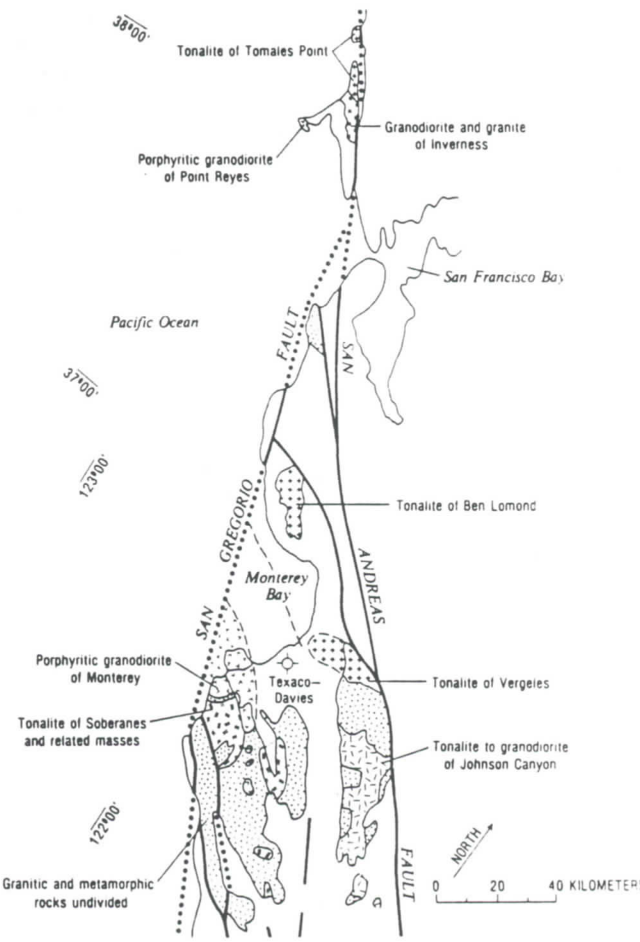

Figure 8. Generalized geologic map showing selected basement rocks of the Salinian block.

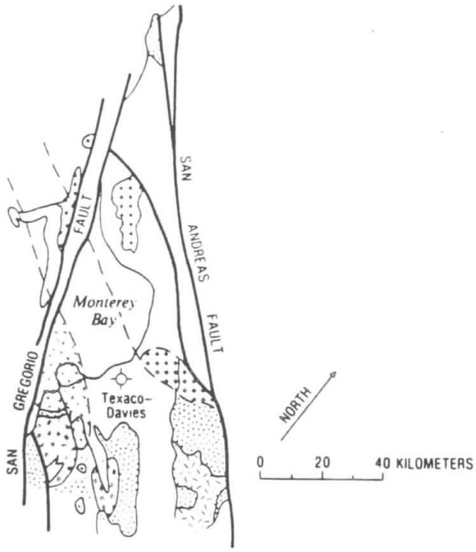

Figure 9. Generalized geologic map showing distribution of tonalites of Tomales Point, Ben Lomond, and Vergeles (cross-pattern) and porphyritic granodiorites of Point Reyes and Monterey (v-pattern) after restoration of about 150 km (94 mi) of right-slip on the San Gregorio fault. Other map patterns the same as on figure 8.

the northern granitic masses but is more similar to that of the Monterey mass, from which we believe that it has been displaced.

Paleocene Sequences

The Point Reyes Conglomerate of Galloway (1977) of the Point Reyes Peninsula is more similar to the Carmelo Formation of Bowen (1965) of the Monterey Peninsula than to the Locatelli Formation of the Santa Cruz Mountains area (fig. 12).

Around Carmel Bay just south of Monterey, the Carmelo Formation rests depositionally upon and is locally faulted against the porphyritic granodiorite basement (Clark and others, 1974). This Paleocene sequence is as much as 220 m (720 ft) thick and consists mainly of thin- to thick-bedded and graded arkosic sandstone and graded pebble and cobble conglomerate (fig. 10). Porphyritic granodiorite clasts predominate in lower conglomerate beds on the north side of the Bay, whereas red, green, purple, and black porphyritic siliceous volcanic clasts dominate higher in the sequence.

Paleocurrents are variable but suggest a westward flow (Nili-Esfahani, 1965). Nili-Esfahani (1965) and Howell and Vedder (1978) believe that these sediments were laid down as part of the canyon or inner fan facies of a submarine fan complex. An arenaceous foraminiferal

SYSTEM	SERIES	STAGE	Rock unit	Lithology	Thickness meters (feet)	Description
QUATERNARY	PLEIST		Aromas Sand		60 (200)	Yellowish-brown to grayish-orange fine sand; nonmarine
QUATERNARY / TERTIARY	PLIO?-PLEIST		Paso Robles Formation		150 (500)	Light gray gravel, sand, and clay; nonmarine
TERTIARY	MIOCENE		Santa Margarita (?) Formation		150 (500)	Very thick bedded white coarse- to fine-grained friable arkosic sandstone
TERTIARY	MIOCENE	Type Delmontian	Monterey Formation: Canyon del Rey Diatomite Member of Bowen (1965)		250 (830)	Very thick bedded and faintly laminated whitish diatomite with thin interbeds and lenses of waxy-brown opaline chert and with few thick interbeds of gray pumicite (=Tmd of Clark and others, 1974)
TERTIARY	MIOCENE	Mohnian	Monterey Formation: Aguajito Shale Member of Bowen (1965)		600 (2000)	Thin-bedded, light-brown to white porcelanite with very thin clay shale partings between porcelanite beds and with thin interbeds of waxy-yellow to brown opaline chert. Contains few thin, dark-brown bentonite interbeds and rare thin phosphatic oolite interbeds in lower part (=Tm of Clark and others, 1974)
TERTIARY	MIOCENE / OLIGOCENE	Luisian			30 (100)	Thin-bedded yellowish-brown semisiliceous mudstone with interbedded siltstone (=Tml of Clark and others, 1974)
TERTIARY	OLIGOCENE	Luisian	Monterey Formation: Los Laureles Ss. Mbr. of Bowen (1965)		60 (200)	Thick-bedded medium- to fine-grained buff-weathering arkosic sandstone (=Tus of Clark and others, 1974)
TERTIARY	OLIGOCENE		Carmeloite of Lawson (1893)		20 (65)	Flows and flow-breccias of basalt. Age 27m.y.
TERTIARY	PALEOCENE	Ynezian	Carmelo Formation of Bowen (1965)		220 (720)	Thin- to thick-bedded and graded arkosic sandstone; graded pebble and cobble conglomerate with porphyritic granodiorite and red, green, purple, and black porphyritic volcanic clasts
			Unconformity			
CRETACEOUS AND OLDER			Salinian basement			Porphyritic granodiorite of Monterey with K-feldspar phenocrysts 3 to 10 cm long; to south and east, grades through granodiorite (Cachagua mass of Ross, 1976) into hornblende-biotite quartz diorite (Soberanes Point mass of Ross, 1976)

Figure 10. Composite stratigraphic column for the Monterey Peninsula. Stratigraphic nomenclature modified from Bowen (1965); Clark and others (1974); and Greene and Clark (1979).

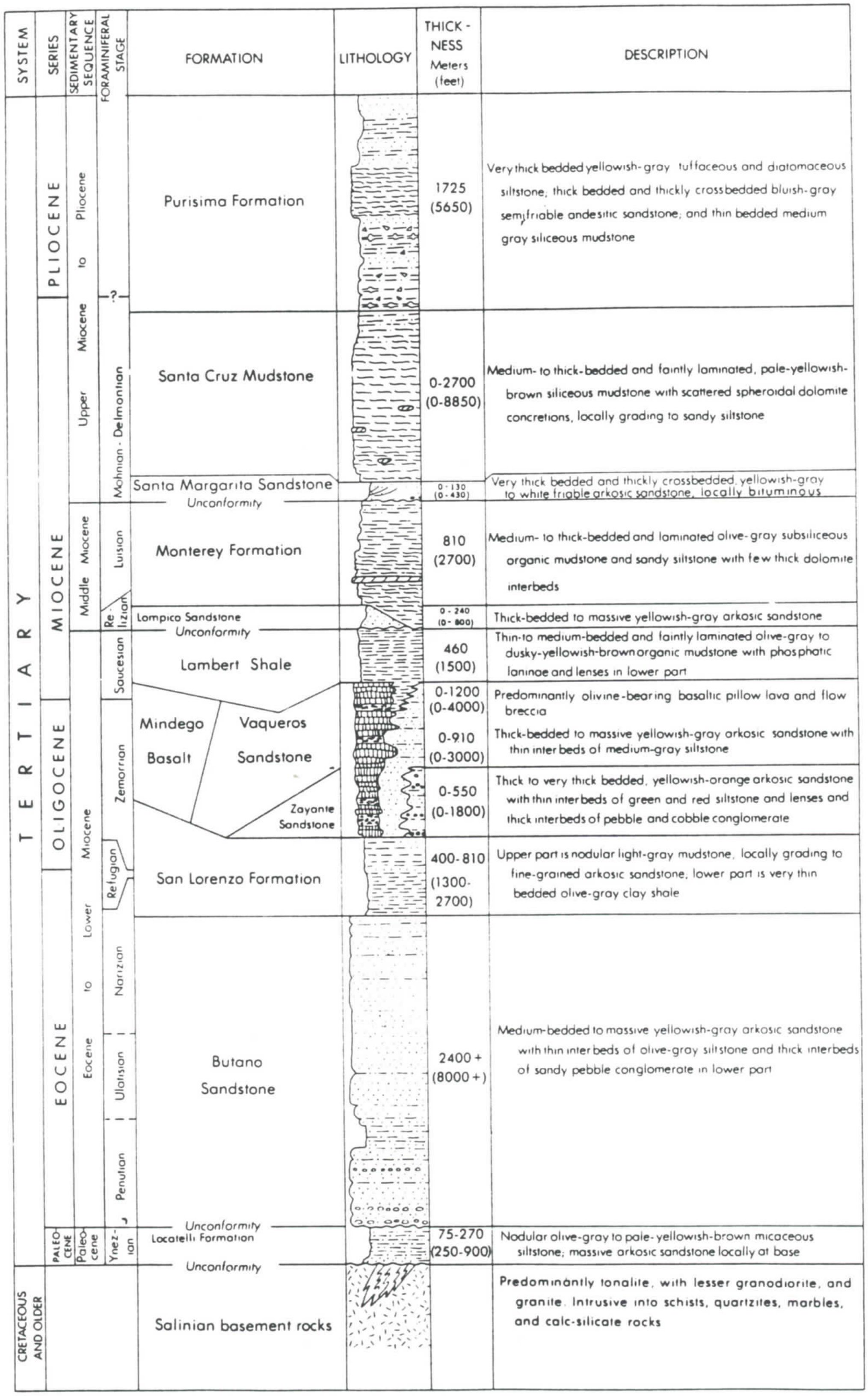

Figure 11. Composite geologic section in the Santa Cruz Mountains northeast of the San Gregorio fault. Stratigraphy from Clark and Brabb (1978) and Clark (1981).

assemblage collected and identified by Clark (listed in Bowen, 1965, p. 51) from near the base of the section at Point Lobos is diagnostic of bathyal depths and of a Paleocene (Ynezian) Age.

Thus, in terms of lithology, paleocurrent direction, facies, and fauna the Carmelo Formation and the Point Reyes Conglomerate are very similar and were probably derived from the same source and laid down in the same embayment.

The Locatelli Formation of the Santa Cruz Mountains (fig. 11), which Graham and Dickinson (1978) matched with the Point Reyes Conglomerate, yields a similar arenaceous foraminiferal fauna and is contemporaneous with both the Point Reyes Conglomerate and the Carmelo Formation, but lithologically does not resemble either of these formations. Noteworthy is the total absence in the Locatelli of both porphyritic granodiorite clasts and porphyritic silicic volcanic clasts.

Howell and Vedder (1978), on the other hand, after restoring 70 km (44 mi) of right slip on the San Gregorio fault, postulate that the Pigeon Point Formation of the Santa Cruz Mountains was deposited in the same embayment as the Carmelo Formation. These two formations are similar in gross lithology and facies, although the Pigeon Point lacks the distinctive porphyritic granodiorite clasts--a difference which might be explained by its southwesterly to southeasterly transport direction.

These two formations, however, are not contemporaneous. The Pigeon Point Formation is entirely Late Cretaceous (Campanian and Maestrichtian), with Cretaceous mollusks having been collected from its uppermost shallow-marine beds (Graham and Dickinson, 1978, p. 18). The arenaceous foraminifers collected by Clark from near the base of the Carmelo Formation are diagnostic of the Paleocene (Ynezian). In the Santa Cruz Mountains, Clark (1981, p. 9) has found planktic foraminifers associated with an identical Ynezian arenaceous assemblage that are diagnostic of late Paleocene (P4-P5 Zone) age. Thus, the Carmelo Formation is most probably of late Paleocene age and is not coeval, even in part, with the Pigeon Point Formation.

Oligocene Basalt Flows

Thin flows and flow-breccias of basalt are discontinuously exposed around Carmel Bay and to the east along Carmel Valley (Clark and others, 1974). Termed "carmeloite" by Lawson (1893), these rocks are typically olivine basalt in which the olivine phenocrysts have been altered to distinctive reddish-brown iddingsite.

At Arrowhead Point on the north side of Carmel Bay, the basalt locally intrudes the Carmelo Formation of Paleocene age; whereas inland, basalt flows appear to be overlain by sandstone beds of Luisian (middle Miocene) age. Nowhere is the basalt seen intruding middle or upper Miocene rocks. Recent potassium-argon dating of two basalt samples from Arrowhead Point yields dates of 27.0 ± 0.8 m.y. and 27.1 ± 0.8 m.y. (G. Brent Dalrymple, written commun., 1980). These dates indicate an Oligocene age for these flows.

Possibly correlative volcanic rocks west of the San Gregorio fault crop out in the Santa Cruz Mountains, 70 to 80 km (44 to 50 mi) to the north, and also have been penetrated in the subsurface of the Point Reyes Peninsula, 160 km (100 mi) to the north.

The volcanic rocks west of the San Gregorio fault in the Santa Cruz Mountains crop out east of Ano Nuevo Point and at Pescadero Beach, where they were included in the Vaqueros(?) Formation by Clark and Brabb (1978). Although highly altered, these volcanic rocks in the Santa Cruz Mountains apparently lacked olivine and are more felsic than those of the Carmel Bay area. Additionally, they are probably younger, for the andesitic breccias at Pescadero Beach overlie sandstone beds that yield Macrochlamis magnolia, which is diagnostic of late Zemorrian or early Saucesian (late Oligocene or early Miocene) age (Clark, 1981, p 38).

On the Point Reyes Peninsula, the Standard Tevis No.1 well near Double Point is reported (R. C. Blaisdell, oral commun., 1978) to have penetrated basalt between a depth of 1,502 and 1,506 m (4,925 and 4,940 ft) beneath the Monterey Formation and above beds of early Eocene or Paleocene age. The stratigraphic position of this basalt is similar, but unfortunately a sample was not available for comparison to the basalt around Carmel Bay.

Middle and Upper Miocene Sequences

The middle and upper Miocene rocks of the Point Reyes Peninsula and Monterey area are similar transgressive Luisian and Mohnian sequences (figs. 6 and 10). Both have basal transgressive arkosic sandstone beds that are as much as 60 m (200 ft) thick and are locally overlain by mudstone beds that yield similar Valvulineria californica Zone benthic foraminifers of Luisian age. As much as 60 m (200 ft) of the lower Monterey section west of Inverness Ridge may be assigned to the Luisian, whereas in the vicinity of Carmel as much as 100 m (330 ft) of the Monterey is Luisian.

Elsewhere in both areas, the lower beds of the siliceous Monterey are Mohnian and the thick porcelanite sections are Mohnian. The few thin bentonite interbeds and the rare phosphatic oolite interbeds that were mapped near Monterey were not seen at Point Reyes. Otherwise, the siliceous sections are very similar. The upper diatomaceous beds (the Canyon del Rey Diatomite Member of Bowen, 1965) that are conformable upon the porcelanite beds at Monterey are absent at Point Reyes.

The original distribution of these Monterey rocks in both areas is difficult to determine because of subsequent erosion and burial by younger sediments. Siliceous Monterey rocks continue northward under Monterey Bay from the Monterey Peninsula to the south wall of the Monterey submarine canyon (Greene and Clark, 1979, fig. 4), whereas much of the northern Monterey Bay and Santa Cruz Mountain area was probably emergent between middle and late Miocene time (Greene and Clark, 1979, p. 292).

Matching the postulated northern limit of Mohnian porcelaneous Monterey in Monterey Bay with the northern limit of known Mohnian porcelaneous Monterey on the Point Reyes Peninsula suggests a minimum of about 160 km (100 mi) of right-slip on the San Gregorio fault since Mohnian (late Miocene) time.

Upper Miocene and Pliocene Sequences

Glauconitic sandstone, siliceous mudstone, and siltstone sequence of the Point Reyes Peninsula are herein assigned to the Santa Margarita Sandstone, Santa Cruz Mudstone, and Purisima Formation because they are similar, lithologically and faunally, to these units mapped in the Santa Cruz Mountains to the south (fig. 11). In both areas, the sequence is also identical, a relatively thin, transgressive, shallow-marine arkosic sandstone (Santa Margarita Sandstone) conformably overlain by a thick, deeper-marine siliceous mudstone (Santa Cruz Mudstone) that locally yields Bolivina obliqua. The siliceous mudstone, in turn, is conformably overlain by a shallow marine siltstone and mudstone unit (Purisima Formation) that in both areas yields a similar cetacean fauna (Repenning and

Tedford, 1977, p. 15) and includes in its lower part a latest Miocene diatom flora. Lithic sandstone interbeds within the correlative Purisima siltstone sections of both areas contain similar distinctive heavy mineral suites of green, brown, and basaltic hornblende, hypersthene, and augite.

Although the upper Miocene and Pliocene sequences of both areas are very similar, areally restricted cross-fault ties are lacking.

In the northern Santa Cruz Mountains northwest of Ben Lomond Mountain, the basal transgressive Santa Margarita Sandstone is bituminous, glauconitic, and highly bioturbated. This bituminous-glauconitic-bioturbated facies grades southward into a bituminous-bioturbated facies, which in turn grades farther southward into a thickly cross-bedded, non-bituminous facies. This latter facies is well exposed in the sand pits of the San Lorenzo Valley area, where it locally includes an Astrodapsis biostrome and is as much as 130 m (425 ft) thick.

Only the bituminous-glauconitic-bioturbated facies crops out on the Point Reyes Peninsula, where it is discontinuously exposed from the seacliffs at Double Point northward to Drakes Bay. The essential mineralogy of sandstone samples from this facies of both areas is similiar.

Overlying the bituminous-glauconitic-bioturbated sandstone in the northern Santa Cruz Mountains is more than 2,000 m (6,560 ft) of Santa Cruz Mudstone that is truncated to the west by the San Gregorio fault. This thickness continues northward at least into the La Honda quadrangle, where Touring (1959, plate 12) indicates that the Texas Steele No. 1 well, located about 1 km (0.6 mi) east of the San Gregorio fault (fig. 12), penetrated about 2,400 m (7,870 ft) of this mudstone (his Monterey Formation) but did not reach its base.

On the Point Reyes Peninsula as much as 2,000 m (6,560 ft) of the Santa Cruz Mudstone occurs stratigraphically above and south of the bituminous-glauconitic-bioturbated sandstone exposure at Double Point. Restoration of about 70 km (44 mi) of right-slip on the San Gregorio fault would juxtapose these thick Santa Cruz Mudstone sections (fig. 12).

TIMING OF MOVEMENT

The match of the granitic basement rocks and of the overlying Paleocene and middle and upper Miocene sequences of the Point Reyes and Monterey Peninsulas suggests that the San Gregorio fault was not active during formation of these rocks and that right-slip was initiated after the porcelaneous and cherty beds of the Monterey Formation (the Aguajito Shale Member of Bowen, 1965; see fig. 10) were laid down in Mohnian (late Miocene) time.

Recent radiometric dating (Obradovich and Naeser, 1981) indicates that the type Monterey Formation spans the interval from 15 m.y.b.p. to perhaps 8 m.y.b.p. A fission-track age for zircons from an ash bed near the base of the Canyon del Rey Diatomite Member of Bowen (1965) places an upper age limit on the porcelaneous and cherty beds of the Monterey of 11.3 ± 0.9 m.y. (Obradovich and Naeser, 1981, p. 89).

Right-slip on the San Gregorio fault probably started between 12 and 11 m.y.b.p. and certainly before 10 m.y.b.p., which is the lower age limit suggested for the Santa Margarita Formation of the Santa Cruz Mountains (Repenning and Tedford, 1977, p. 25). The regional sub-Santa Margarita unconformity in the Santa Cruz Mountains and Point Reyes Peninsula probably records this event.

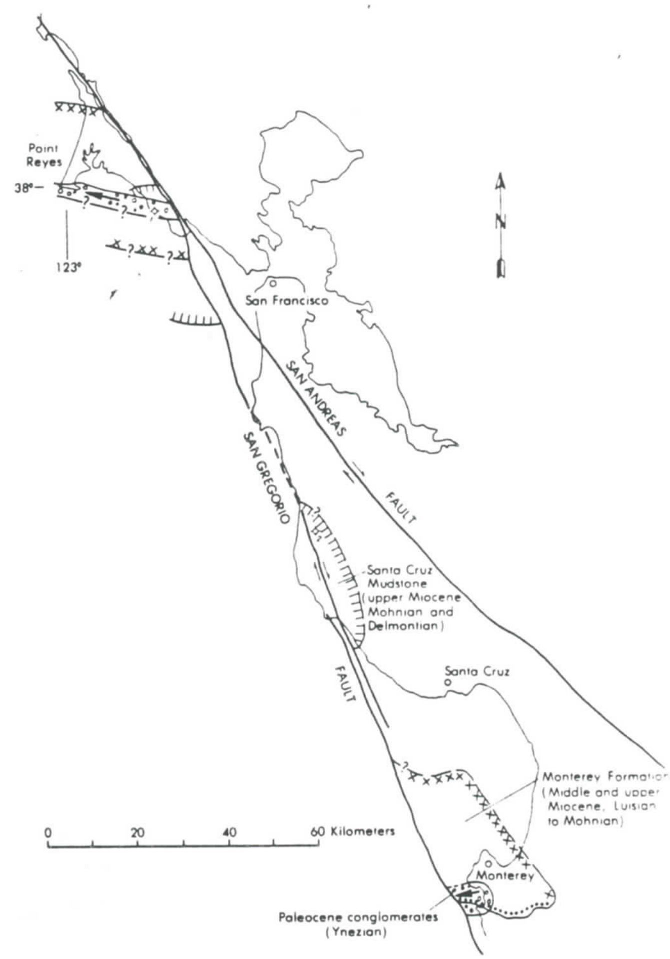

Figure 12. Distribution of offset Tertiary sequences of Point Reyes (PR), Santa Cruz Mountains (SC) and Monterey (M) areas. (1) Standard Tevis 1 well; (2) Texas Steele 1 well.

Offset of the thick Santa Cruz Mudstone sections of the Point Reyes Peninsula and Santa Cruz Mountains occurred after deposition of at least part of the Bolivina obliqua Zone, which spans a time interval of 6.5 m.y. to 4 m.y. (Obradovich and Naeser, 1981). Glauconite from the base of the Purisima Formation, where locally near Santa Cruz it is unconformable upon the Bolivinia obliqua—bearing type Santa Cruz Mudstone, has been dated at 6.7 ± 0.6 m.y. (Clark, 1981, p. 33). Thus, total right-slip on the San Gregorio fault of about 150 km (94 mi) has occurred in the last 11 to 12 m.y. with about 70 km (44 mi) of this in the last 6 to 6.5 m.y.

The San Gregorio fault is still active, and at an estimated Quaternary slip rate of 0.63 to 1.30 cm/yr (Weber and Lajoie, 1977), 150 km (94 mi) of slip on this fault would have accumulated in 23.8 m.y. to 11.5 m.y. Thus, this higher slip rate is in remarkable agreement with the rate necessary to produce the 150 km of displacement that we postulate since deposition of the porcelaneous and cherty beds of the Monterey Formation.

RELATIONSHIP TO SAN ANDREAS FAULT HISTORY

The possibility of as much as 560 km (350 mi) of displacement along the San Andreas fault was first suggested by Hill and Dibblee (1953), who estimated progressively smaller offsets of sequentially younger rocks.

Their maximum displacement was based on a postulated offset of basement terranes. The northernmost onland exposures of Salinian basement at Bodega Head appeared to have been displaced a minimum of 510 km (319 mi) from the probable buried western limit of Sierran basement to the south (Graham and Dickinson, 1978, p. 20).

Comparing the petrology of these granitic terranes, Ross (1978), on the other hand, suggested that the Salinian basement was an "orphan" that was not offset from the southern Sierra Nevada. Recent paleomagnetic findings that have been summarized by Page (1982) tend to confirm Ross' postulate and indicate that the Salinian block is probably out of place and has traveled northward since Cretaceous emplacement several thousand kilometers. Page (1982) suggests that the Salinian block probably arrived in California between 55 and 38 m.y.b.p., and that right-slip on the San Andreas fault system resulting from Pacific--North American transform interaction commenced about 29 m.y.b.p.

Maximum offset of 305 km (190 mi) along the San Andreas fault of central California is supported by cross-ties provided by a late Eocene subsea fan (Nilsen and Clarke, 1975), an early Miocene shoreline (Turner, 1969), and 23.5 m.y.-old Pinnacles and Neenach Volcanics (Huffman, 1972; Matthews, 1973). As all three of these units are displaced the same amount, right-slip did not begin in central California on the present San Andreas until post-early Miocene time.

Although the San Andreas fault splays into a series of subparallel faults south of the Transverse Ranges, the collective offset of basement rocks on the San Andreas, San Gabriel, and San Jacinto faults is about 330 km (206 mi) (Crowell, 1981). Thus, the maximum documented displacement on the central and southern segments of the San Andreas fault is essentially the same. Because of this similarity of total offset together with the apparent mismatch of Salinian and Sierran granitic rocks that was the basis for larger postulated displacements, the existence of pre-Eocene movements on the present San Andreas fault is in doubt.

North of San Francisco, however, total offset along the San Andreas fault has been greater then that to the south because of the additive effect of right-slip on the San Gregorio fault. The addition of the 150 km (94 mi) of offset that we assume on the San Gregorio produces a total displacement on the northern segment of the San Andreas fault of 455 km (284 mi).

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