NORTHERN CALIFORNIA GEOLOGICAL SOCIETY

Geology of the Point Reyes Area, California

Saturday, September 27, 2003

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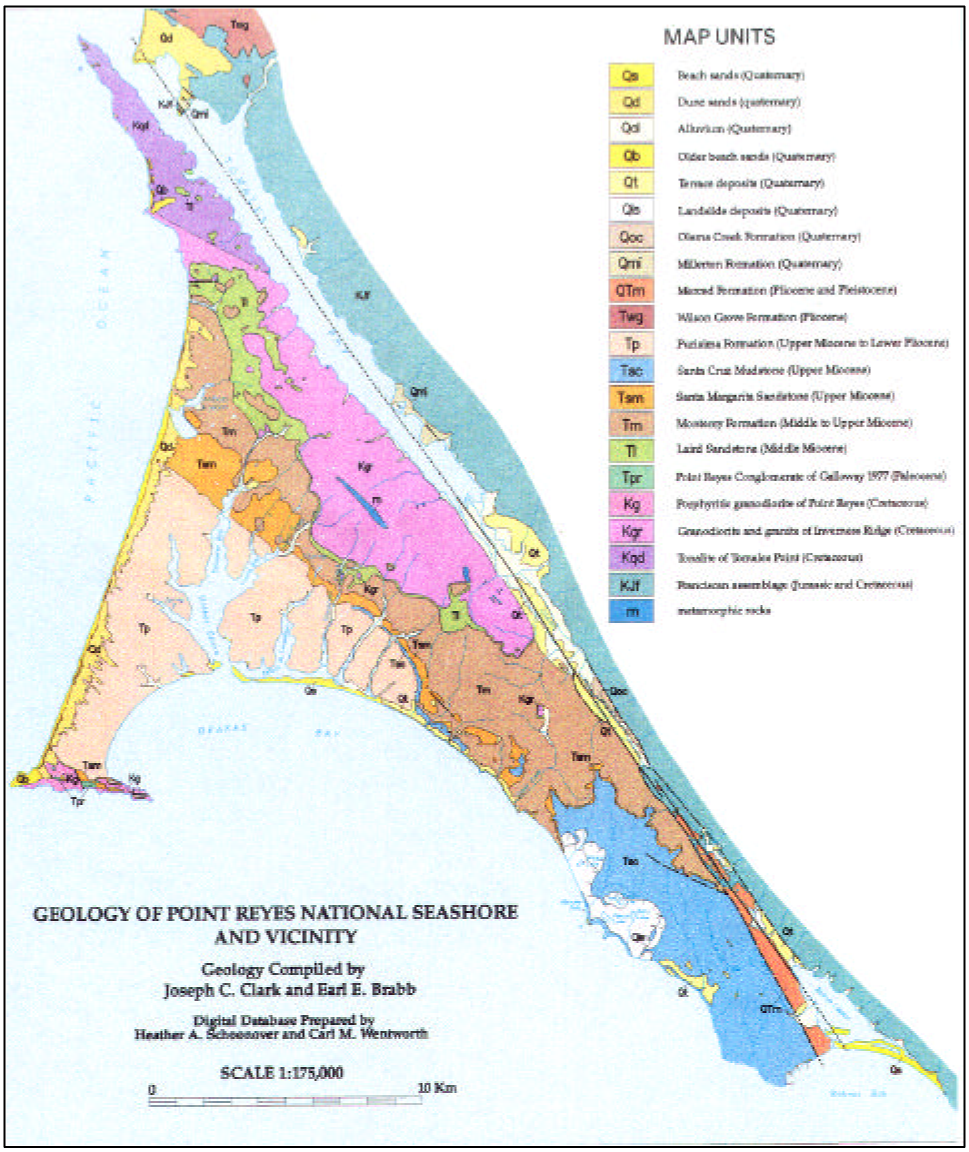


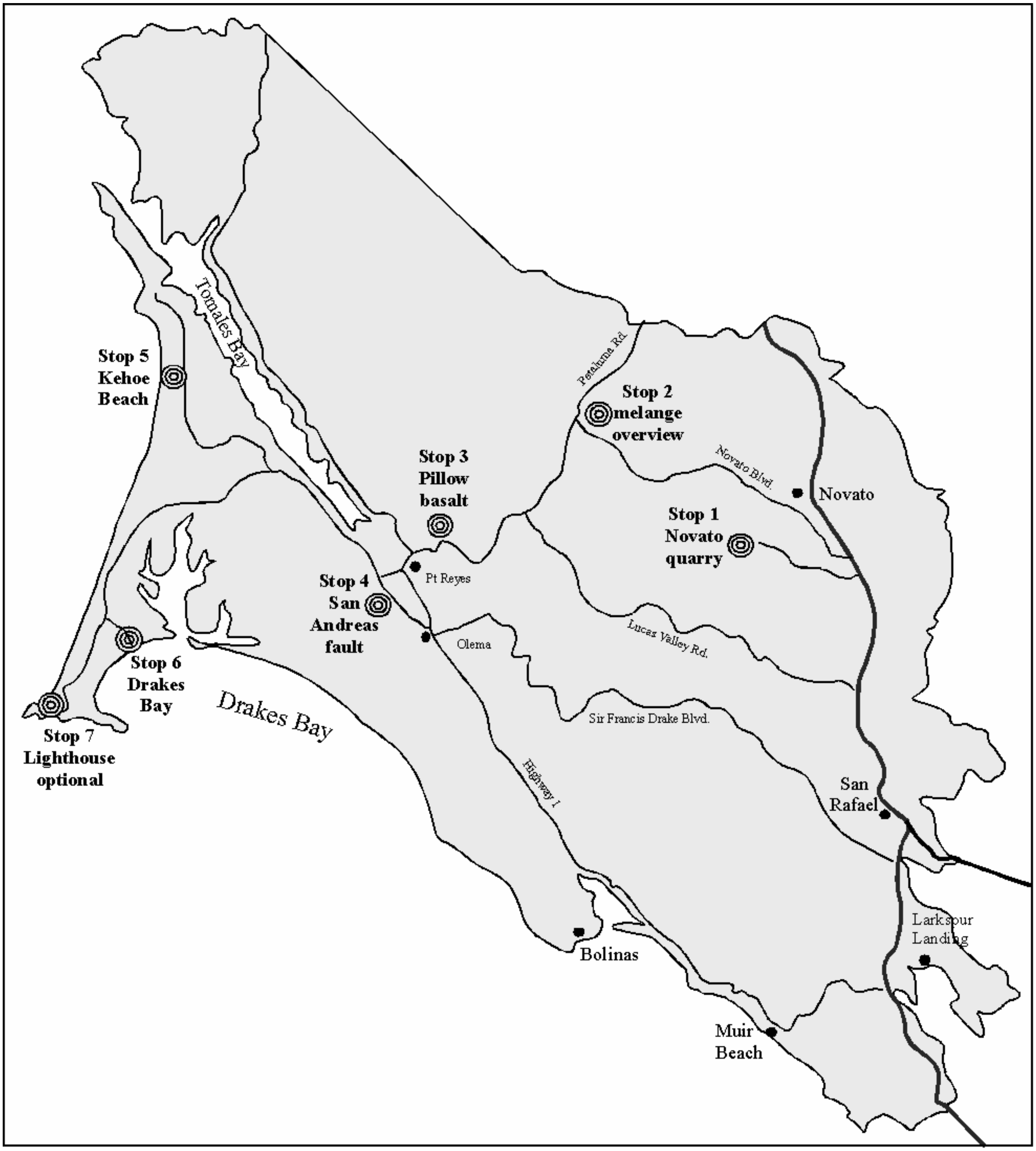


Figure 1

Stop 1. Novato quarry; Novato Quarry terrane; broken formation
Stop 2. Classic "knocker" topography typical of Franciscan melange.
Stop 3. Pillow Basalts, Nicassio Reservoir terrane, Black Mountain
Stop 4. Point Reyes visitor center; San Andreas Fault.
Stop 5. Kehoe Beach; granitic basement and overlying transgressive marine sequence.
Stop 6. Drakes Beach; diatomaceous mudstone, upper Miocene/Pliocene Purisima Formation.
Stop 7. (optional) Point Reyes lighthouse; Paleocene/Eocene turbidites; submarine channel.

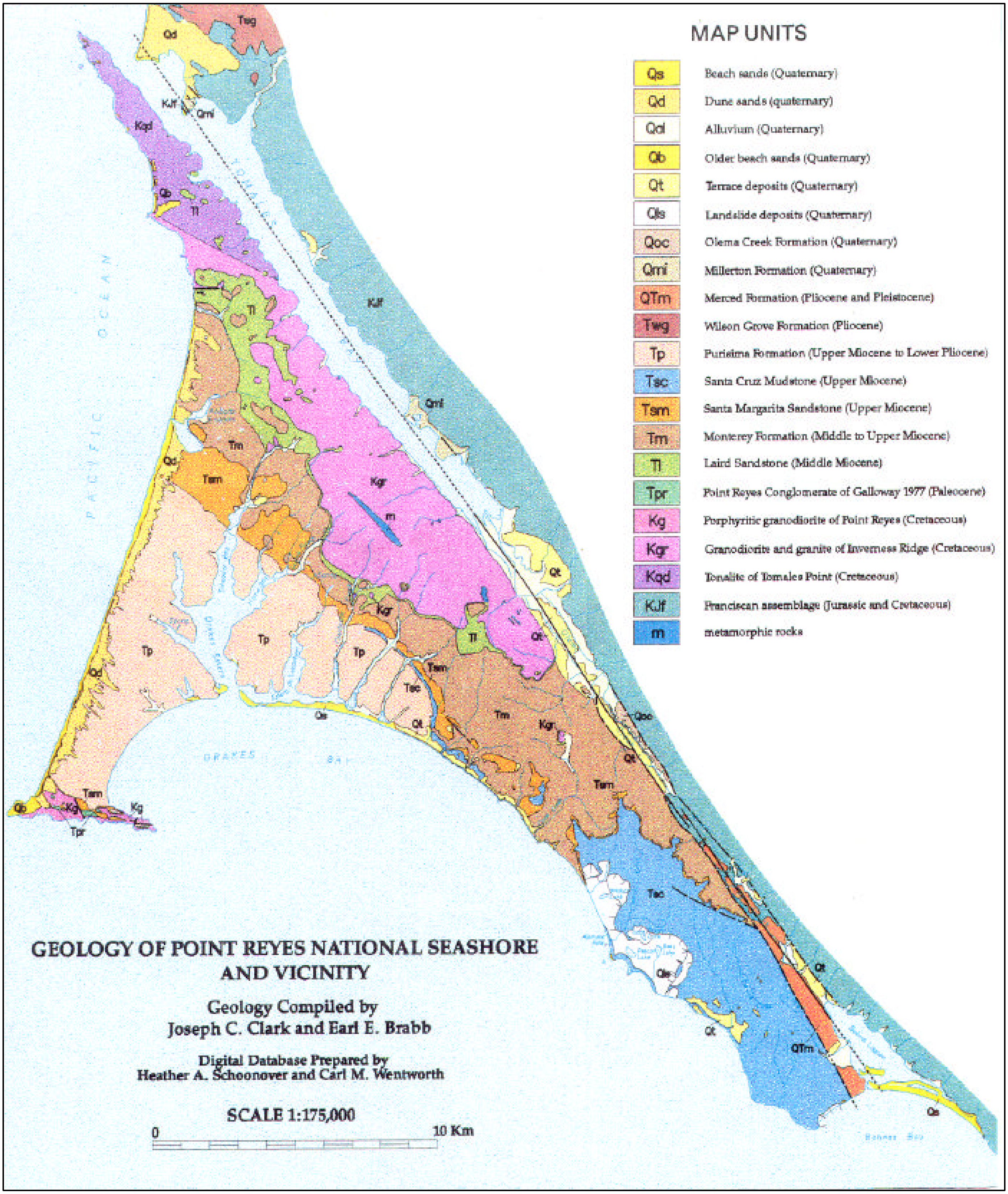


Figure 2. Geologic map of the Point Reyes area (from NCGS field trip handout, 1996; a newer edition is available on the web at http://wrgis.wr.usgs.gov/docs/geologic/ca/california.html).

Overview

The Point Reyes area is a great place for a geologic field trip. Aside from its natural beauty, it contains a wide range of geologic features, including: a piece of Salinian granitics with overlying sedimentary cover; a well-known portion of the San Andreas fault; and a diverse suite of rocks of the Franciscan complex. All of these have been well studied and the resultant publications have great bearing on our interpretation of the geologic history of California.

For example, the sedimentary cover overlying the granitics on Point Reyes have proved to be a major piece of the puzzle in understanding fault movement in northern and central California. In the early eighties, Clark et al (1984) published compelling evidence for displacement of ~150 km along the San Gregorio/Hosgri fault, based on comparisons of rocks in Monterey and the Santa Cruz Mountains with those on the Point Reyes Peninsula. Subsequent work by several workers has supported this conclusion.

The Point Reyes area is also a key to the origin of the Franciscan. Because of its proximity to major universities and especially the U.S. Geological Survey, the area has been studied in detail and became important in the development of the terrane concept. Regardless of what you may think about the origin of terranes, the recognition of terranes as mappable units was a major step forward in subdividing the Franciscan into units smaller than the previously recognized "coastal, central and metamorphic" belts. A large part of this work was done in Marin County and we will visit three different terranes on this trip

Finally, the San Andreas Fault at Point Reyes is historically significant. It is very close to the epicenter of the 1906 earthquake and was studied in detail by G.K. Gilbert shortly after the quake. At the Point Reyes visitors center we will visit the famous area where he mapped displacement of a barn and fence. Recent work on the fault in the area includes trenching across fault traces and studies of recent sediments by core and outcrop.

With all this to see, it is not surprising that the Point Reyes area has been the scene of many field trips in the past. Notably, the NCGS ran pre- and post-meeting field trips to Point Reyes in conjunction with the AAPG annual meeting that was held in San Francisco in 1990 (also see Clark and others, 1991).

Recently, new digital maps of the Point Reyes Peninsula (Clark and Brabb, 2000) and of Marin County (Blake, Graymer, and Jones, 2000) with text descriptions have been published on the internet by the USGS*. These wonderful maps can be downloaded and manipulated on your home computers and you will see several examples in this guidebook and on the field trip.

This guidebook is mainly a compilation of previous work. Thanks to Bruce Bilodeau and Stephanie Davis for permission to use parts of their 1990 guidebook. Also thanks to Clark Blake, Earl Brabb, and Joe Clark for their work on the area, used liberally in this guidebook. Finally, thanks to Will Schweller for helping put together a previous edition of this guidebook for a field trip run for ChevronTexaco in the Fall of 2002.

*http://wrgis.wr.usgs.gov/docs/geologic/ca/california.html

Geologic Setting

The area near Point Reyes consists of two contrasting geologic provinces separated by the San Andreas fault (Figure 2). East of the San Andreas fault, the Coast Ranges consist mainly of the Franciscan Complex, which is a belt of highly deformed and variably metamorphosed greywacke, mudstone, volcanics, limestone, and chert. The Franciscan Complex is generally accepted to be an accretionary wedge formed above an eastward-dipping subduction zone when the western edge of North America was mainly a convergent plate boundary from the late Jurassic to the Miocene (Fig. 3). In contrast, the area west of the San Andreas, mainly Point Reyes itself, has a Cretaceous granitic basement similar to the roots of the Sierra Nevada. The granitics are overlain by a small sliver of early Eocene strata (Clark and Brabb, 2000) followed by a thick sequence of Miocene to recent sedimentary rocks, the latter deposited in a transform setting initiated along the California coast ~29 m.y.a.

Tectonic History of Point Reyes (from Bilodeau and Davis, 1990).

The tectonic history of most of the rocks exposed in the Point Reyes area starts in the Late Jurassic. 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. The Great Valley sequence, which now occupies the Sacramento Valley, was being deposited in the fore-arc basin between the continental arc volcanics on the east (now 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 (Figures 3 and 4).

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 near the rise 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.

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 (strike-slip) fault formed at the boundary between the Pacific and North American plates in order to accommodate their relative motion. This transform fault system grew with time and appears to have stepped continentward. The active part of the fault is currently known as the San Andreas Fault. Since its inception 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 Ma.; Clark and others, 1984), 315 to 320 km in central California since Early Miocene (post-Saucesian, ca. 20 Ma.; Graham and others, 1989) and 330 km in southern California since the Late Miocene (8 Ma.; 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) proposed about 150 km of slip on the San Gregorio fault just south of Point Reyes, giving a total slip in the Point Reyes area of 455 km.

Origin of the Salinian Block (from Bilodeau and Davis, 1990)

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 block appears to have originated as a piece of continental crust that broke off the continent to the south and slid northward into the middle of rocks deposited within a subduction zone.

Studies of offset along Salinia's bounding faults can help explain the block's origin. The San Andreas Fault, which bounds the block on the northeast, is better exposed than the faults that bound the southwest side and has been the subject of intense scrutiny by geologists.

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 Ma., Clark and others, 1984). When the post Eocene offset is restored (post 36.6 Ma.), 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 fault to explain the apparent pre-Eocene 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. Offset along the same fault occurring before 12 Ma. could help to explain the troublesome 230 km.

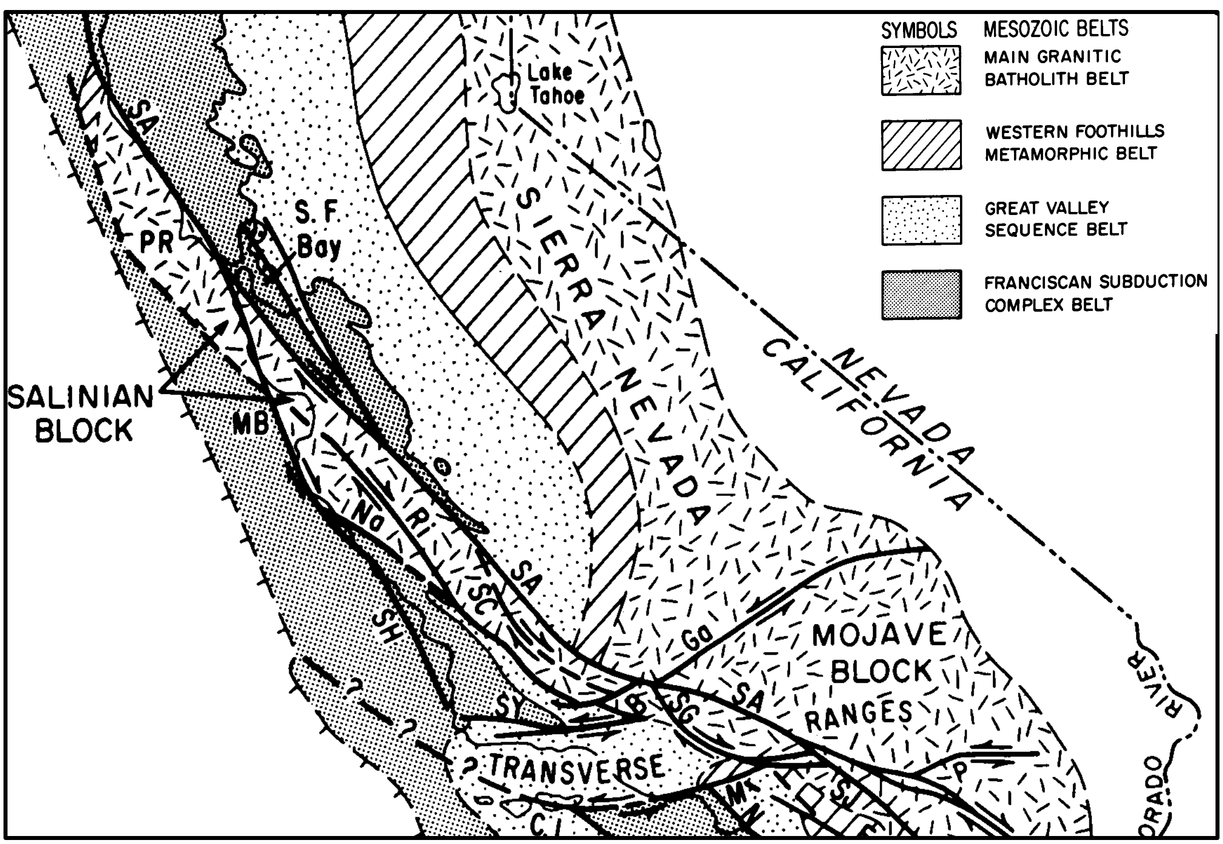


Figure 3. Principle Mesozoic lithotectonic belts in California (Dickinson, 1983).

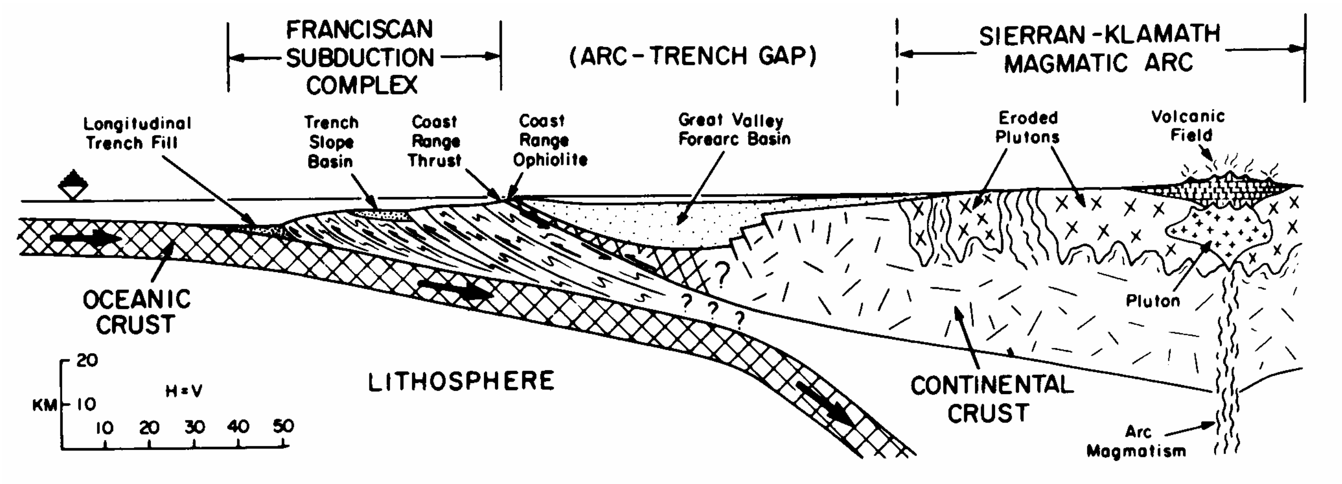


Figure 4. Cross-section of the western margin of California during Late Cretaceous/Early Paleogene time (from Dickinson and others 1982).

Franciscan Complex (from Bilodeau and Davis, 1990)

The Franciscan assemblage is a belt of highly deformed and variably metamorphosed graywacke, mudstone, volcanics, limestone and chert occupying the coast of California from Santa Catalina Island to Oregon. Early subdivision of the Franciscan was into three major units that trend roughly parallel with the coast (Figure 5). From west to east they are the Coastal Belt, the Central Melange Belt, and the Metamorphic or Yolla Bolly Belt (Blake and Jones, 1981).

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 that is highly faulted, a structure known as a broken formation. The Coastal Belt appears to have been thrust under the Central Belt along a major shear zone.

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. Fossils recovered from the matrix have shown this zone to be Late Jurassic to Early Cretaceous in age, but the blocks are 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.

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 but probably also includes Upper Jurassic rocks as well. The unit is bounded on the east by the Coast Range "thrust," a sharp, often sheared contact with the relatively unmetamorphosed Great Valley Sequence, which appears to structurally overlie the Franciscan.

Franciscan Terranes

In the early eighties, mapping in the Franciscan using the "terrane concept" led to the recognition of a number of "tectonostratigraphic" terranes defined as having a 'stratigraphy that is different than its neighbor' (Blake et al, 1982 and 1984). Subsequent work has resulted in many changes to the initial subdivisions. Within Marin county, eight terranes are recognized (Blake, Graymer and Jones, 2000) as shown and described below (Fig. 6 and Table 1).

Since terranes were first mapped in the Franciscan, there have been two opposing view on their origin. One camp, lead by Dickinson (see also Cloos, 1990), argued that the Franciscan, at least from Late Jurassic through the Cretaceous, was part of a relatively simple, interrelated three-part system represented by the coeval Franciscan subduction complex, the Great Valley sequence forearc basin, and the Sierra Nevada arc. The other group, championed by Blake and Jones and others argued that much of the Franciscan may have originated far to the south and carried northward by strike-slip faulting or sea-floor spreading before docking in the Franciscan.

The Dickinson camp clearly recognized that some terranes or parts of terranes were far traveled, including the Permanente limestone, parts of the Marin headlands terrane and possibly the volcanics of the Nicassio Reservoir terrane. These are considered to be parts of seamounts or the uppermost part of seafloor crust that could easily be incorporated into an accretionary prism (see Stop 3 text for further discussion). So the argument really revolves around terranes that are composed mainly of sandstone and shale, and note that sandstone and shale make up ~90% of the Franciscan (Bailey, Irwin and Jones, 1964).

Evidence to support the argument that large volumes of sandstone and shale within the Franciscan came from areas unrelated to the Great Valley sequence and Sierra Nevada arc are not strong. Early arguments involved provenance as determined from sandstone and conglomerate and comparison of sand/shale ratios between the Franciscan and Great Valley sequence. These arguments are unconvincing as outlined by Cloos (1990). In addition, paleomagnetic evidence from sand/shale sequences has proved to be ambiguous (Blake et al, 2000).

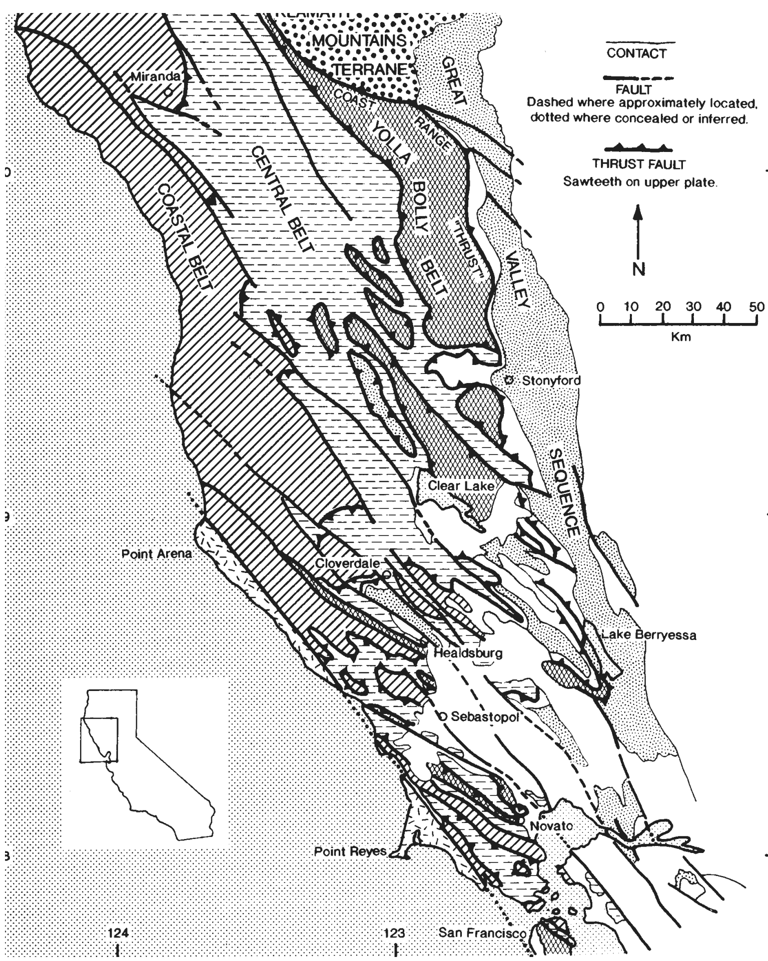


Figure 5. Lithotectonic belts of the Franciscan complex, northern California Coast Ranges (adapted from Blake and Jones, 1981)

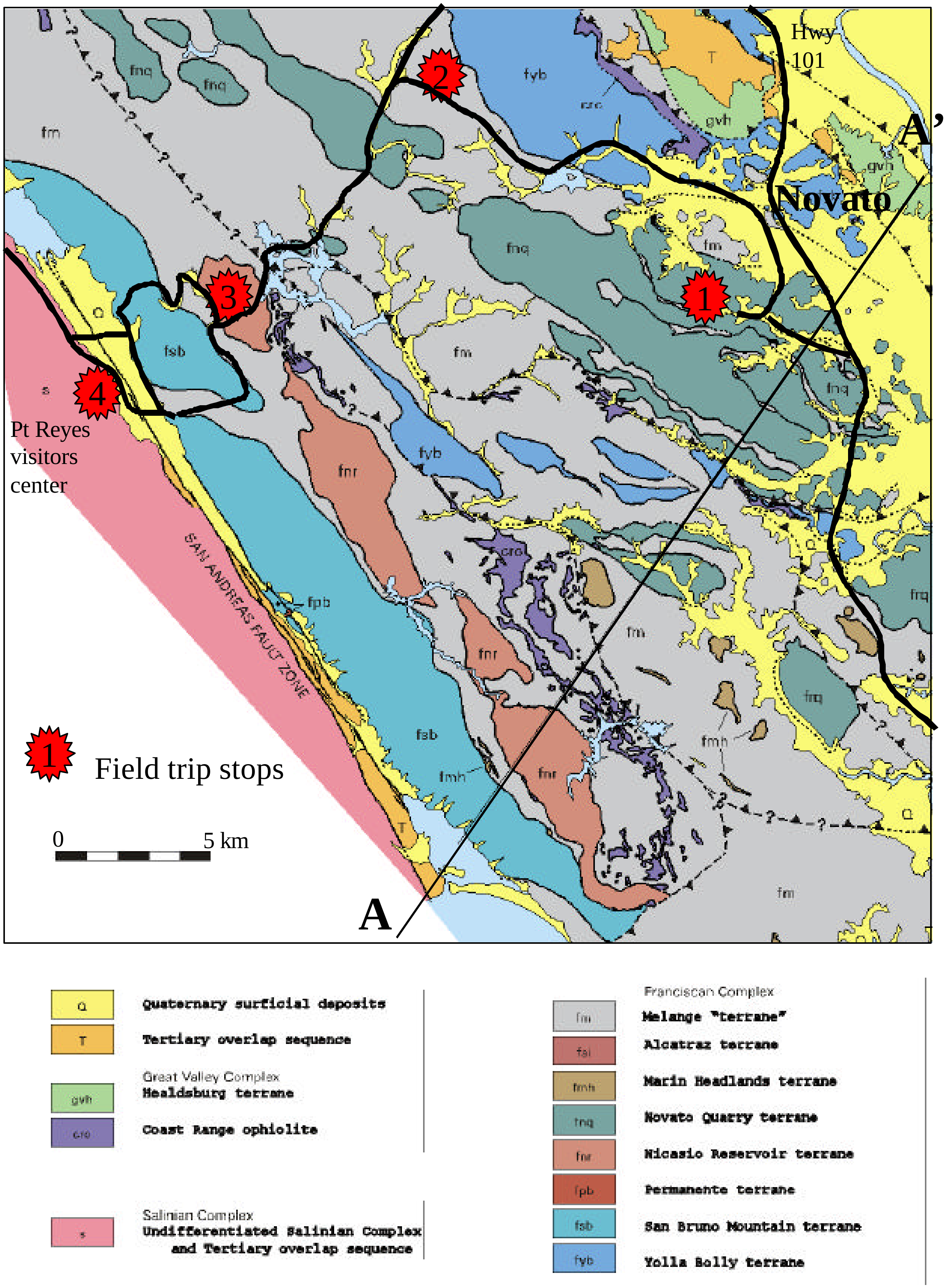


Figure 6. Terrane map of part of Marin county. Adapted from Blake, Graymer and Jones, 2000. Cross-section shown in Figure 7.

Description of mapped units shown in Figure 6.

(condensed from Blake, Graymer and Jones, 2000; please see original map pamphlet for complete descriptions and references)

__Great Valley complex__

Healdsburg terrane

Lower Cretaceous sedimentary rocks *that crop out in the mapped area* that have similar lithology, structural state, and fossil content to strata found to the east along the west side of the Great Valley….. are assigned to the Healdsburg terrane.

Coast Range ophiolite Although outcrops of the Coast Range ophiolite in other parts of the San Francisco Bay region include all the rock types that make up the ophiolite suite (pillow basalt, sheeted diabase, static gabbro, cumulate gabbro, peridotite), the only lithology present in the map area is serpentinite. All serpentinite in the map area is herein considered to be part of or derived from the Coast Range ophiolite.

__Franciscan complex__

Marin Headlands terrane The rocks at the Marin Headlands consist of pillow basalt overlain by radiolarian chert, which in turn is overlain by sandstone (graywacke) and shale. *Numerous studies* …..suggest that the basalt formed *near the equator* during the Early Jurassic (about 190 Ma) at a mid-ocean ridge, was covered by a blanket of radiolarian chert during it's long (nearly 100 m.y.) trip across the ocean, and eventually reached a trench where the chert was covered by Cretaceous turbidites derived from a volcanic arc

Yolla Bolly terrane

The Yolla Bolly terrane is one of the most widespread and distinctive Franciscan complex terranes in the map area. It consists of metagraywacke, metachert, and metabasalt, all containing abundant blueschist-facies minerals such as lawsonite, jadeitic pyroxene, and metamorphic aragonite. In addition, the metagraywackes are characterized by a weak to pronounced foliation. These rocks have been correlated with the type Yolla Bolly terrane of northern California based on similarities in lithology, sandstone composition, age, and metamorphic state.

Alcatraz terrane

On Alcatraz and Yerba Buena Islands, north and east of San Francisco in San Francisco Bay, and in eastern San Francisco, another graywacke-rich terrane (broken formation) crops out that lacks the metamorphic minerals and foliation seen in the Yolla Bolly terrane and instead contains metamorphic prehnite and pumpellyite.

Novato Quarry terrane

The Novato Quarry terrane forms a relatively narrow, discontinuous northwest-trending belt between the San Andreas and Hayward faults. It consists largely of thin-bedded turbidites with local channel deposits of massive sandstone. Although the strata are in many places folded and locally disrupted (broken formation), they are nearly everywhere well bedded. Like the Alcatraz terrane, the sandstone contains metamorphic prehnite and pumpellyite.

San Bruno Mountain terrane

Another graywacke terrane of unknown age crops out in San Francisco and along Bolinas Ridge in western Marin County (mostly in Bolinas and Inverness quadrangles). It is characterized by relatively well-bedded turbidites containing abundant detrital K-spar plus widespread veins of hydrothermal quartz and adularia that are spatially related to rhyolite dikes and other intrusive bodies.

Nicasio Reservoir terrane

An elongate belt of pillow basalt, gabbro, and minor radiolarian chert can be followed from Mt. Tamalpais north to Black Mountain in western Marin County. ….. studies suggest that the Nicasio Reservoir terrane represents a fragment of a Late Jurassic- Early Cretaceous ocean island (similar to Hawaii) that formed about 20 degrees south of its present position.

Permanente terrane

Several blocks of gray limestone with replacement chert crop out along the San Andreas Fault Zone, north of Bolinas (Bolinas quadrangle). These are identical, lithologically and paleontologically, to the Calera Limestone of the San Francisco Peninsula …. assigned to the Permanente terrane. The Permanente terrane consists of accreted sea-mounts that formed near the equator.

Central "terrane" (Mélange)

All of the previously-described Franciscan and Great Valley complex terranes in the map area are tectonically enclosed in an argillite matrix mélange that has been called the Central belt. However, these rocks do not comprise a terrane in the strict tectonostratigraphic sense, in that they are the result of combining rocks from several terranes. Most of the mélange matrix consists of sheared mudstone (argillite) and lithic sandstone, within which are mixed numerous blocks and slabs of greenstone, chert, metamorphic rocks, serpentinite, and other rocks.

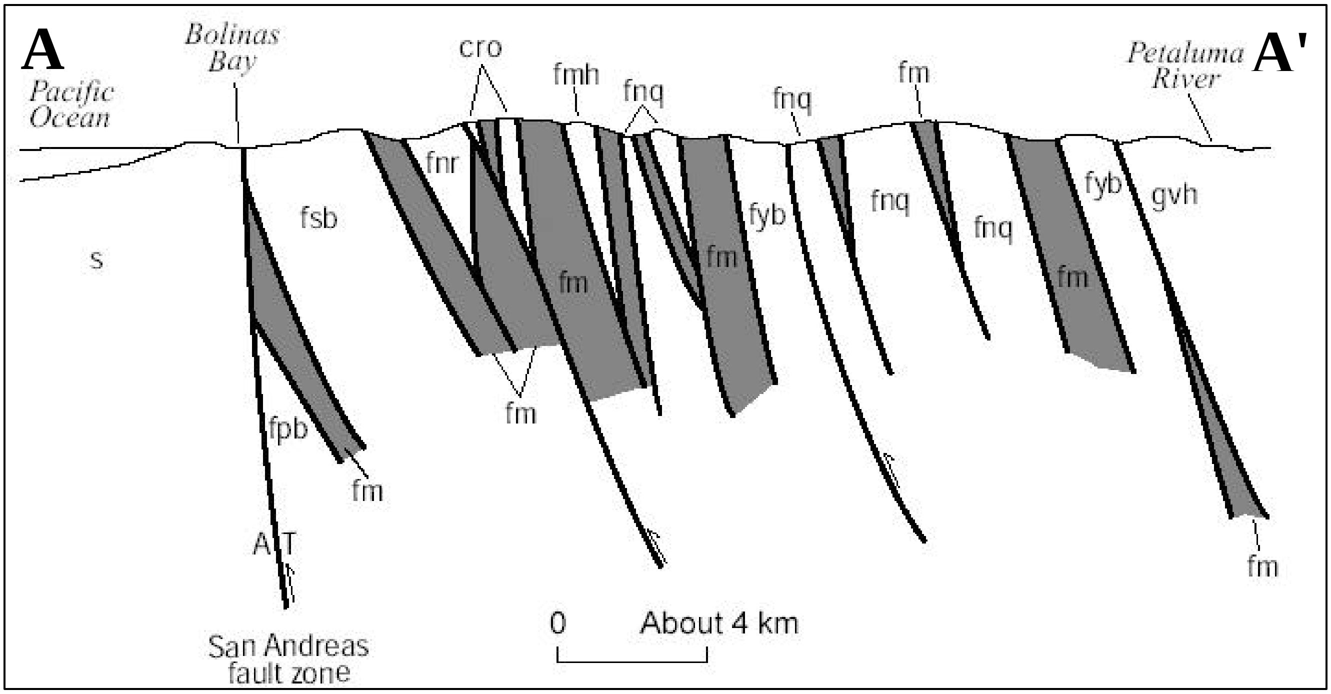


Figure 7. Cross-section A-A' showing Marin County terranes (from Blake et al, 2000); for location and key, see map shown in Figure 6.

Franciscan Field trip stops

On this trip, we visit two terranes and the Central belt melange. Note that all of the terranes in the mapped area (Fig.6) are enclosed within melange (gray areas with "fm" on map).

Stop 1. Novato Quarry (walk from parking lot of Indian Valley School)

The Novato quarry is the type area for the Novato Quarry terrane. It consists mainly of well-bedded sandstone and shale that has been sheared and folded. Shear zones and faults tend to be parallel to subparallel to bedding. The resulting structural style is called "broken formation" and is very common throughout the Franciscan, being particularly well displayed throughout most of the Coastal belt. In broken formation, most of the faults and shear zones are thought to form early on in the subduction process such that the planes of faulting and shearing are roughly parallel to the subducting slab.

The strata here are mainly thin-bedded turbidites. Graded bedding is not easy to see here because of the induration of the beds and generally fine grain size. However, we will look for graded beds to see if any of the outcrop is overturned.

On our return to the vehicles, we will walk up a side road and examine a block of red chert. The chert contains many microfractures that have been healed by recrystallized silica. We can look for radiolaria with our hand lenses (on a wet surface they typically appear as circular gray areas typically ~1mm in diameter) but this particular block is probably barren. We will discuss the several possibilities for the tectonic emplacement of this block within the Novato Quarry terrane.

Stop 2. Central belt Melange (corner of Petaluma road & Novato Blvd (Figure 1)

As we drive to Stop 2 look for "knockers" which are blocks of resistant Franciscan rock types "floating" in sheared mudstone (Figure. 8). Blocks include variably metamorphosed chert, sandstone, bedded sandstone/shale, volcanics and ultrabasic rocks, including serpentinite.

It is clear that much of the mixing in melange was done tectonically, but disruption by soft sediment slumping or olistostroms also played a role that was probably significant based on studies of modern trench slopes. In addition, recent studies of serpentinite-bearing mud volcanoes in the Marianas trench and elsewhere give us a new way of incorporating ultramafic rocks into higher levels of a subduction complex (e.g. Fryer et al, 1999).

Stop 3. Nicasio Reservoir terrane, Pillow Basalts (from Bilodeau and Davis, 1990; not all of their figures are included)

This stop contains one of the best exposures of pillow basalts in the Franciscan Complex (Figure 9). The road is narrow, however, and can be dangerous for large groups, so please be careful!

The pillowed sequence at Black Mountain dips northeast and is 1 to 2 km (3000-6000 ft) thick. The pillows have diameters of up to 2 m and tube shapes when viewed in three-dimensions. The outcrop also contains small amounts of brecciated pillows and diabase feeder dike systems and numerous minor faults and veins. Most basalt pillows are separated from one another by a fine-grained, locally intensely sheared matrix composed of pillow fragments and altered debris, which was probably largely basaltic glass. Small pods or discontinuous layers of radiolarian-bearing chert and manganese-stained shale confirm the deep-sea origin of these basalt pillows, as does the general lack of vesicles that are common in basalt pillows formed in shallow water. The upper surface of most of the basalt pillows is convex whereas the lower surface is molded onto the tops of the underlying pillows. This distinctive cross-sectional shape indicates stratigraphic tops are toward the northeast.

Origin of Pillow Structures in Basalt Flows Basalts (from Bilodeau and Davis, 1990)

Pillow structures commonly form at the front of basaltic lava flows that are advancing underwater. Dredging, ocean-bottom photographs and submarine observations show that pillow lava is very widespread at the ocean spreading ridges and may be the most abundant type of lava flow on earth. Although basalt pillows generally appear to be independent sacks of basalt in two-dimensional outcrops, they are actually elongate cylindrical forms in three dimensions. They are elliptical when seen in cross-section but can be seen to be long sausage shapes if the outcrop shows a longitudinal or map view.

Figure 8. View of typical topography from the central belt of the Franciscan Complex. The prominent outcrops are termed “knockers” and consist of a variety of harder rocks that are irregularly distributed in the dominantly mudstone matrix. Photo by Will Schweller.

Figure 9. Well-exposed pillow basalts of the Nicassio Reservoir terrane.
Photo by Will Schweller.

The pillows have distinct core and rim zones when viewed in cross-section. Swanson and Schiffman (1979) examined two pillows from this locality in detail. They found that the rims contain scattered euhedral phenocrysts of plagioclase and clinopyroxene floating in a finely crystalline groundmass of altered palagonite glass. The rim zone grades into an intermediate zone of crystals, amygdules and a microcrystalline groundmass. The intermediate zone grades into the core which is composed of dendritic to subhedral crystals with minor groundmass and a few large amygdules. The textural contrasts from rim to core reflect progressively slower rates of cooling and crystallization.

The first observations of the active formation of a pillowed lava flow were made in 1971 by scuba divers examining lava from a flow of Kilauea on Hawaii that had entered the ocean. Moore and others (1973) provide photos and a detailed description of the process that is briefly summarized below. Pillows of still molten lava expand, branch and lengthen as lava feeds into the pillow and expands and cracks its outer crust. New crust is continuously formed at opening cracks as the pillow expands and deforms. The lava pressure that causes a flow lobe to grow arises from the lobes upslope connection to larger feeder lava tubes. The process of forming pillows is similar to the squeezing of toothpaste from a tube.

Emplacement of Pillow Basalts into the Franciscan Complex Basalts (from Bilodeau and Davis, 1990)

Geochemical analyses of the Nicasio Basalts compiled by Blake and others (1984) show that the bulk composition of a dozen or so samples is tholeiitic and similar to common ocean floor basalts. According to Blake and others (1984, p. 11), the ratios of P_2O_5 to TiO_2 for the Nicasio Basalts are similar to those reported for basalt from either ocean ridges or ocean islands.

Three tectonic settings can be identified for pillowed mafic rocks in the Franciscan: 1) pieces from the overriding Coast Range Ophiolite; 2) pieces of the oceanic crustal layer at the top of a subducted Pacific plate; and 3) seamounts built on ocean crust (e.g. Hawaii) that became detached from the descending plate during subduction.

The seamount setting is probably the most likely origin for the Nicasio pillow basalts. Because no uplift is required, it is immediately apparent as to why it is mechanically easier to accrete pieces of protruding seamounts during subduction than to accrete flat slabs of ocean crust. Seamounts taller than a few kilometers typically rise above the typical interplate shear zone, and therefore may be detached from the subducting plate and accreted into the accretionary complex as relatively coherent masses.

The Nicasio Basalts form three coherent masses that are so large that they are readily mappable. They were probably detached from near the upper part of a seamount that was at least several kilometers tall. Because the three bodies of Nicasio Basalt record similar paleomagnetic poles, it seems likely that they are either all fragments from the same seamount or fragments from a subducted chain of seamounts.

Stop 4: Point Reyes Visitor Center and San Andreas Fault

Figure 10. Raised relief map of the Point Reyes area in the Point Reyes Visitor Center, showing the strongly fault-controlled topography of the area caused by the San Andreas fault.

The 1906 San Francisco Earthquake (from Niemi and Hall, 1990)

At 5:12 A.M. on April 18, 1906, farmers were thrown from their milking stools when the earth began to shake. The magnitude 8.3 (7.8M) San Francisco earthquake ruptured the northern 460 kilometers of the San Andreas fault from San Juan Bautista to offshore Cape Mendocino. Calculations have located the epicenter west of the Golden Gate (Bolt, 1988), although the maximum observed offsets and field epicenter were located in the Olema Valley.

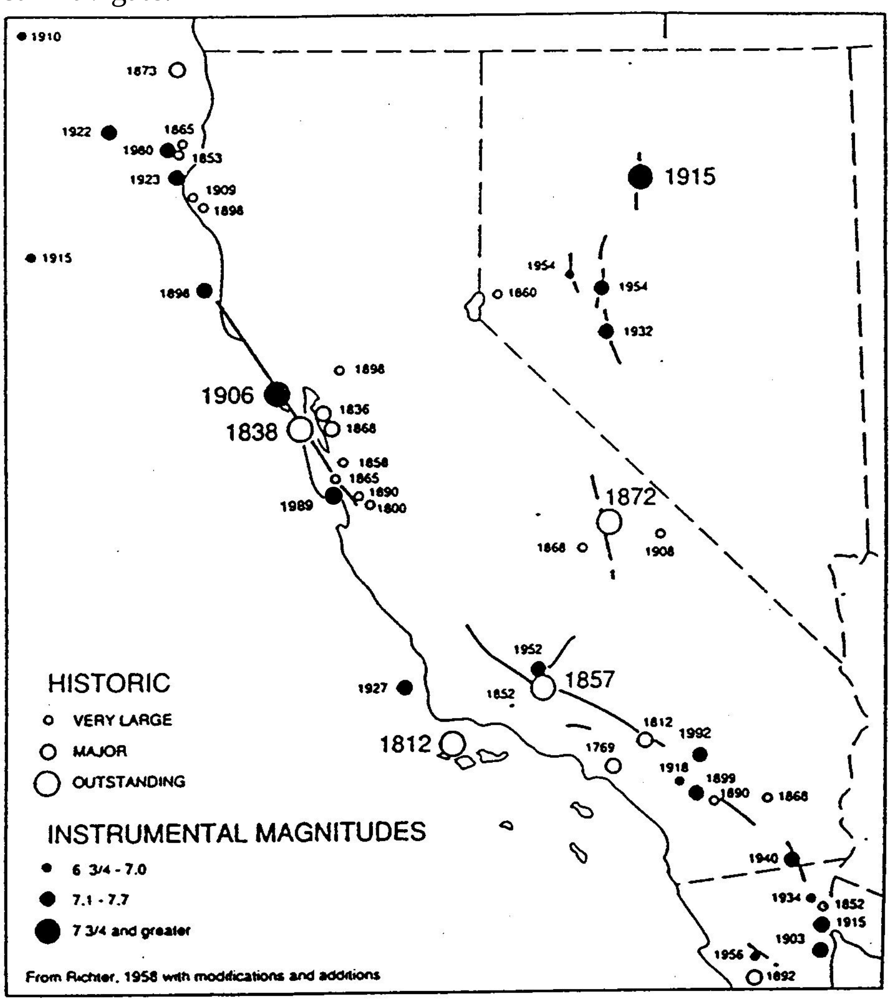
The earthquake was felt over an area of 450,000 square km (175,000 sq mi), from Oregon to Los Angeles and western Nevada (Lawson, 1908). It caused severe damage to buildings close to the fault trace and to structures built on artificial fill and bay mud. The fire that raged in San Francisco for three days after the earthquake caused more damage than the quake itself. The total number of deaths statewide from the disaster was approximately 700. Although the ground shaking was intense along the San Andreas Fault, there were no reported casualties in the Point Reyes area.

Within a few weeks after the earthquake, G.K. Gilbert measured the displacement of fences, roads, rows of trees and other man-made features in Marin County. He recorded right-lateral offsets of 3.4 to 4.6 m north of Bolinas, 4.4 to 4.9 m near the present-day Point Reyes National Seashore headquarters, and 6.1 m on Sir Francis Drake Blvd. near the head of Tomales Bay (Lawson et al, 1908).

Stop 4 Description (from Bilodeau and Davis, 1990)

G.K. Gilbert mapped four displaced cultural features on the Skinner ranch in 1907 to document the 4 to 5 meter offsets produced by the 1906 earthquake. Most of these features are gone today, but the sidehill bench along the trace of the fault is still visible and the "offset fence" has been reproduced on the Earthquake Trail.

The Earthquake Trail 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 his 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.



1769-1992: Large California earthquakes (>6.75)

Figure 11. Map showing the locations of large earthquakes in California since 1776.

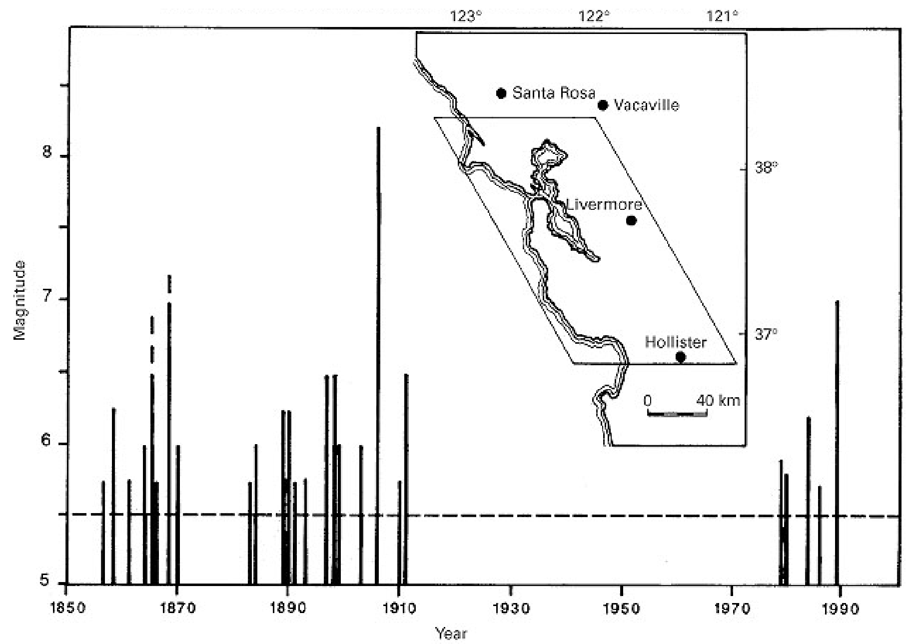


Figure 12. Distribution through time of large earthquakes in the San Francisco area. Note the gap between 1911 and ~1980. Are we beginning another period of more frequent quakes?

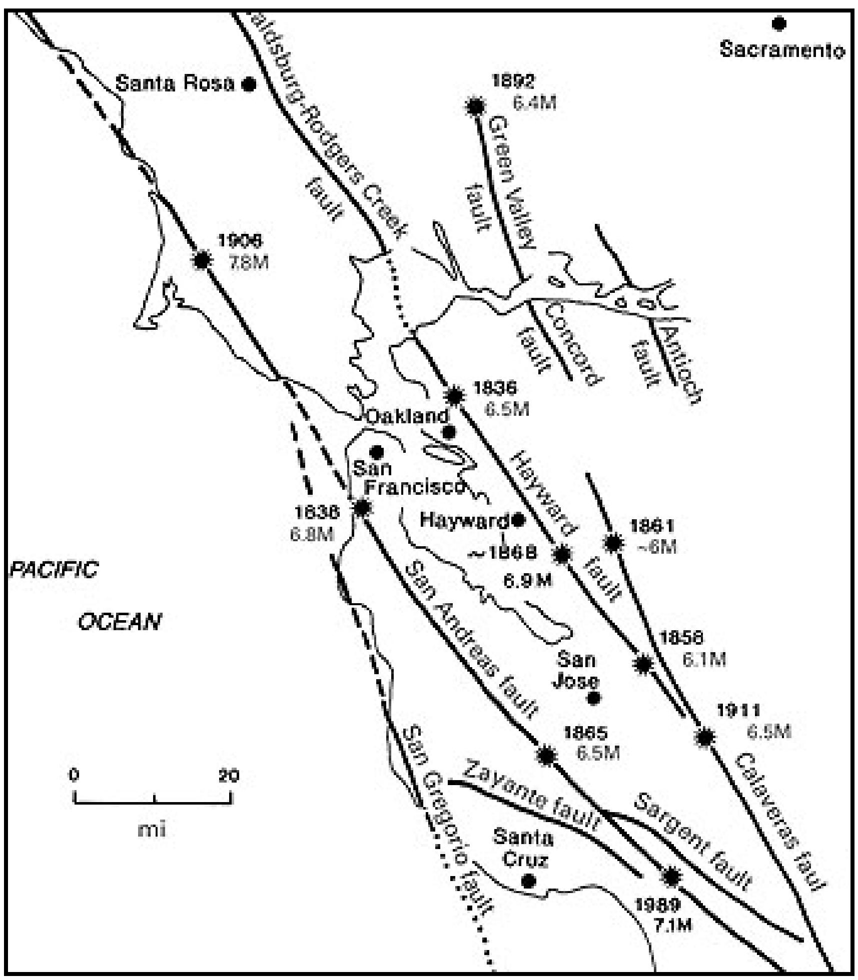


Figure 13. Bay area faults and past large earthquakes.

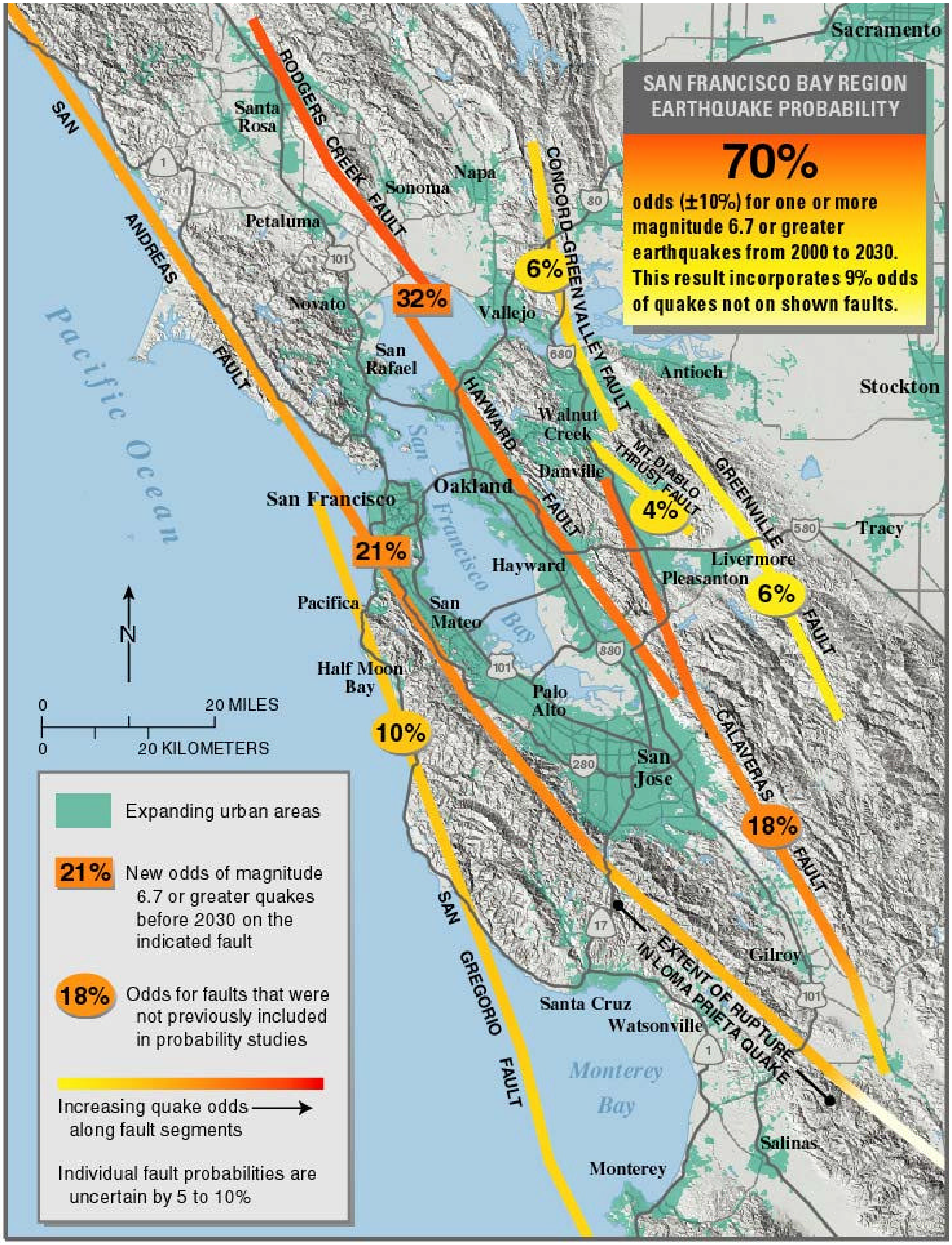


Figure 14. Map with overlays of major active earthquake faults and calculated odds of earthquake recurrences (USGS working group, WG99, http://geopubs.wr.usgs.gov/fact-sheet/fs152-99/).

GEOLOGY OF THE POINT REYES NATIONAL SEASHORE AND VICINITY, MARIN COUNTY, CALIFORNIA: A DIGITAL DATABASE

By J.C. Clark and E.E. Brabb, 2000*

GENERAL GEOLOGY

The Point Reyes Peninsula is a roughly triangular projection of the Marin County coast with an apex at Point Reyes and a base along Tomales Bay and the rift valley of the San Andreas fault zone. This fault zone forms the active tectonic boundary between the Pacific and North American lithospheric plates and here separates Upper Cretaceous granitic and older metamorphic rocks of the Salinian block to the west from Upper Jurassic to Lower Cretaceous graywacke sandstone and melange of the Franciscan complex to the east.

Resting nonconformably upon the crystalline basement of the Point Reyes Peninsula is a composite section of as much as 4,370 m (14,340 ft) of moderately deformed Tertiary marine sedimentary rocks that comprise three sequences, separated by unconformities. The oldest sequence consists of as much as 210 m (700 ft) of the Point Reyes Conglomerate of Galloway (1977) of early Eocene age that rests depositionally upon the porphyritic granodiorite of Point Reyes.

A middle and upper Miocene sedimentary sequence is as much as 1,610 m (5,300 ft.) thick and consists of a basal sandstone unit, the Laird Sandstone, and an overlying porcelanite unit, the Monterey Formation. This Neogene sequence crops out on the southwest slope of Inverness Ridge, where it rests nonconformably upon the granodiorite and granite of Inverness Ridge.

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 youngest sequence is as much as 2,550 m (8,500 ft.) thick and consists of a basal glauconitic sandstone unit, the Santa Margarita Sandstone, a siliceous mudstone unit, the Santa Cruz Mudstone, and an upper siltstone, mudstone, and sandstone unit, the Purisima Formation. Clark and others (1984) applied these formational names from the Santa Cruz Mountains to the correlative units at Point Reyes because of their very similar stratigraphic relationships, lithologies, and fossil faunas and floras.

A complete superpositional section is nowhere exposed on the Point Reyes Peninsula, and good rock exposures are generally restricted to the sea cliffs. Three deep exploration wells (wells 4, 5, and 6, Sheet 1) penetrated thick sections of the upper Miocene and Pliocene sequence and of the middle and upper Miocene sequence (see Oil Test Wells Ê, sheet 1). Additionally, the Chevron Tevis no. 1 well drilled near Double Point (well 4, sheet 1) penetrated 5 m (16 ft) of altered olivine pyroxene basalt beneath the middle and upper Miocene sequence and above as much as 502 m (1,646 ft) of dark shale of early Eocene age (Kris McDougall, written commun., 1997).

The close similarity of the Upper Cretaceous porphyritic granodiorite sand of the lower Eocene and middle and upper Miocene sequences of the Point Reyes and Monterey Peninsulas suggests as much as 150 km (94 mi) of total right slip displacement on the San Gregorio fault in the last 11 Ma. Similarities of the glauconitic Santa Margarita and of the thick Santa Cruz Mudstone sections of the upper Miocene and Pliocene sequences of the Point Reyes Peninsula and of the central Santa Cruz Mountains indicate that 70 to 90 km (44 to 56 mi) of this offset occurred in the last 6 to 8 Ma.

* Map and text can be seen at: http://geopubs.wr.usgs.gov/open-file/of97-456/

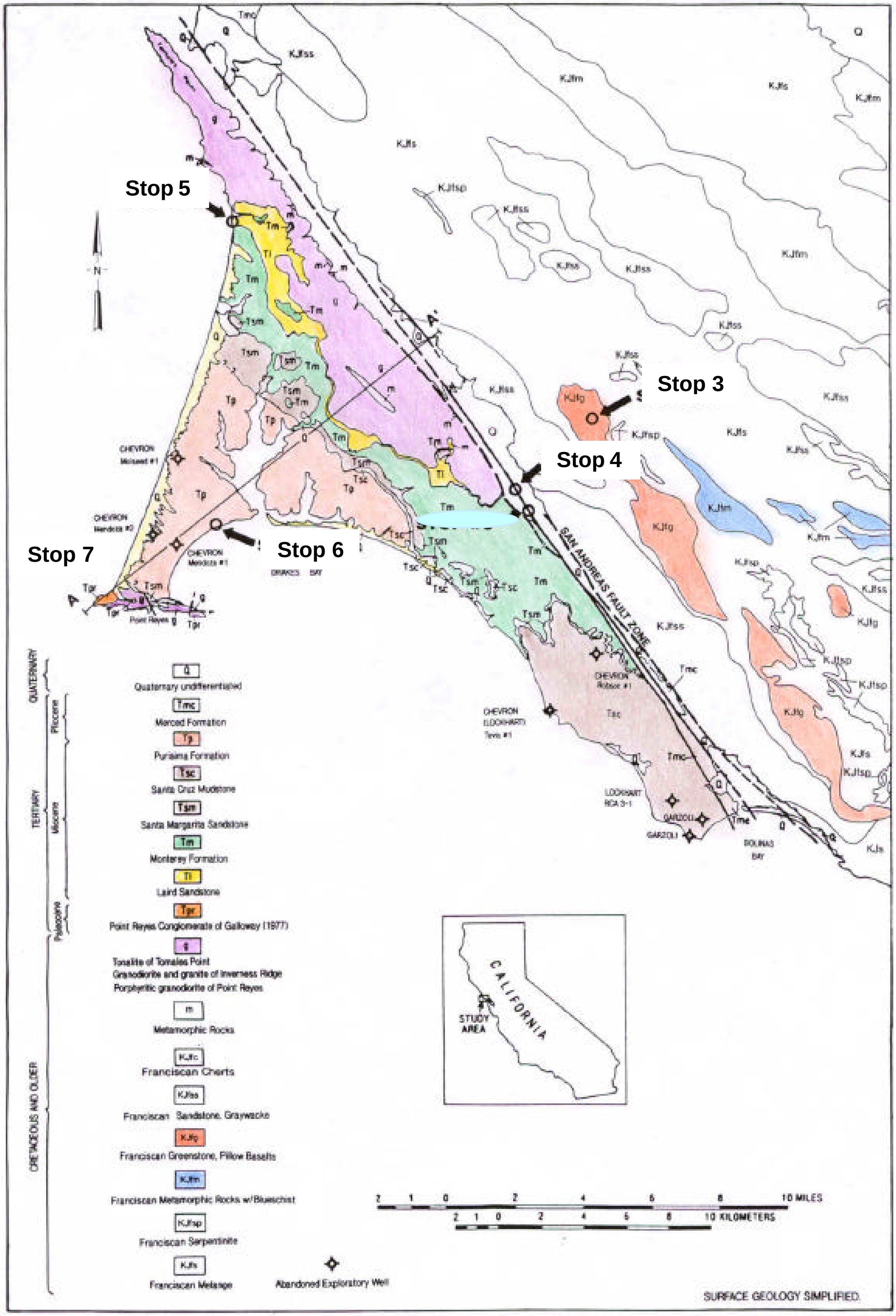


Fig. 15. Geologic map of the Point Reyes area (in Bilodeau and Davis, 1990, modified from Clark and others, 1984, and Blake and others, 1974).

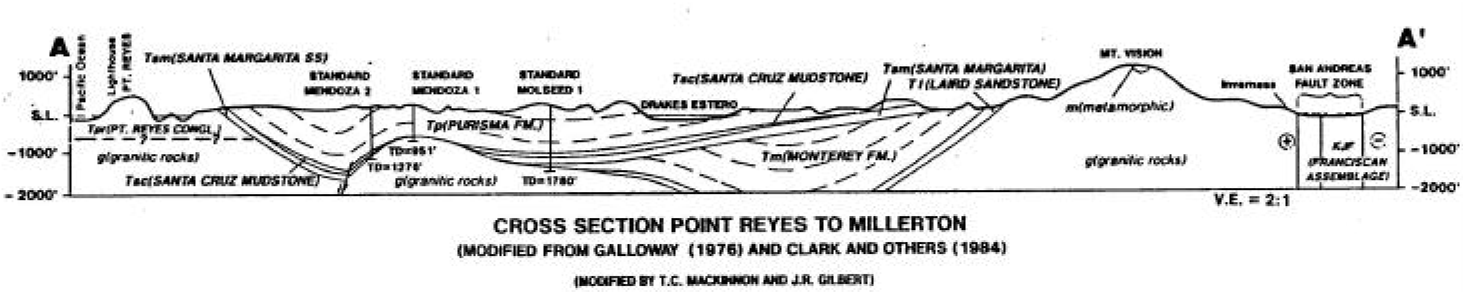


Figure 16. Geologic cross-section of the Point Reyes area; location shown in Figure 15 (in Bilodeau and Davis, 1990, modified from Clark and others, 1984, and Blake and others, 1974).

DESCRIPTION OF ROCK UNITS (continued, J.C. Clark and E.E. Brabb, 2000)

Metamorphic rocks -- Mica schist, impure quartzite, calc-hornfels, and graphitic marble locally containing scheelite occur as inclusions and small roof pendants in the granodiorite and granite of Inverness Ridge. Garnet- and sillimanite-bearing quartzo-feldspathic gneiss and granofels form a septum at McClures Beach between the tonalite of Tomales Point and the granodiorite and granite of Inverness Ridge (Ross, 1977, 1978). Although Cretaceous granitic rocks intrude these metasedimentary rocks, their age is uncertain but is probably Mesozoic or Paleozoic.

Plutonic rocks

Tonalite of Tomales Point -- Hornblende-biotite tonalite that contains dark diorite inclusions forms the basement of Tomales Point. This rock is lithologically similar to the tonalite that crops out at Bodega Head about 10 km to the north, and both are probably part of the same granitic mass (Ross, 1978). K-Ar dating of hornblende in the tonalite of Bodega Head yields an age of 94.3 Ma (Late Cretaceous) (Evernden and Kistler, 1970; recalculated using new constants in Dalrymple, 1979).

Granodiorite and granite of Inverness Ridge -- Granodiorite and granite are exposed along Inverness Ridge, where dikes and masses of aplite and alaskite are locally abundant.

Porphyritic granodiorite of Point Reyes -- Porphyritic granodiorite that crops out at Point Reyes contains K-feldspar phenocrysts that average 2 to 3 cm and are as long as 5 cm; locally this rock is not porphyritic. The granodiorite has 2 to 12 percent biotite and hornblende, about 30 percent quartz, 25 to 35 percent K-feldspar, and the remainder plagioclase. Chemically, it is about 70 percent SiO_2, 15 percent Al_2O_3, 2.6 percent FeO, 2.8 percent CaO, 3.3 percent Na_2O, and 3.4 percent K_2O (from Ross in Clark and others, 1984; and Ross, 1984). K-Ar dating of biotite in this granodiorite gives an age of 82.0 Ma (Late Cretaceous) (Curtis and others,1958; recalculated using new constants in Dalrymple, 1979), and fisson-track dating of sphene from this rock yields ages of 82.7 ± 6.9 and 86.8 ± 7.4 Ma (Late Cretaceous) (Naeser and Ross, 1976).

Point Reyes Conglomerate of Galloway (1977) -- Very thick, graded arkosic sandstone beds and very thick sandy conglomerate beds, locally channeled into the sandstone, rest nonconformably on the porphyritic granodiorite of Point Reyes. The conglomerate consist of 30 to 50 percent subangular, porphyritic, granodiorite clasts as much as 2 to 3 m long, 30 to 40 percent well-rounded purple and black porphyritic siliceous volcanic pebbles and cobbles, and 10 to 20 percent light-colored quartzite pebbles, with lesser red chert and black and green volcanic pebbles. As much as 210 m of section crops out near the Point Reyes lighthouse. These beds were probably laid down in a northwesterly-trending, upper mid-fan submarine channel complex (Clark and others, 1984). Arenaceous benthic foraminifers in one surface sample are typical of bathyal depths and indicated to Galloway (1977) a Paleocene age. McDougall (written commun., 1997) has reinterpreted this fauna and believes that the age is early Eocene, Penutian, coeval with planktic foraminiferal zones P6b to early P9, based on the joint occurrence of Karreriella elongata (=K. media-aguaensis), Pelosina complanata, Silicosigmolina californica, and Spiroplectammina directa (=S. perplexa). McDougall also examined several cores from mudstones in the Chevron Tevis well (#4 on geologic map) in the intervals from 5058 to 6097 feet where the foraminifers are better preserved, more diverse, and contain more index species than the Galloway sample. The Tevis samples are also early Eocene, Penutian, P6b, P8, and P6b to early P9.

Laird Sandstone -- Very-thick-bedded, light-gray, medium-to-fine-grained, biotitic arkosic sandstone with scattered calcareous concretions locally includes a thick boulder granitic conglomerate at base. Rests nonconformably on the granodiorite and granite of Inverness Ridge and on the tonalite of Tomales Point. As much as 64 m thick at Kehoe Beach, this sandstone unit thins to the east to less than 12 m near Lairds Landing on Tomales Bay. Mollusks and echinoids from near the base of the Kehoe Beach section are diagnostic of shallow-marine depths and middle Miocene age (Clark and others, 1991).

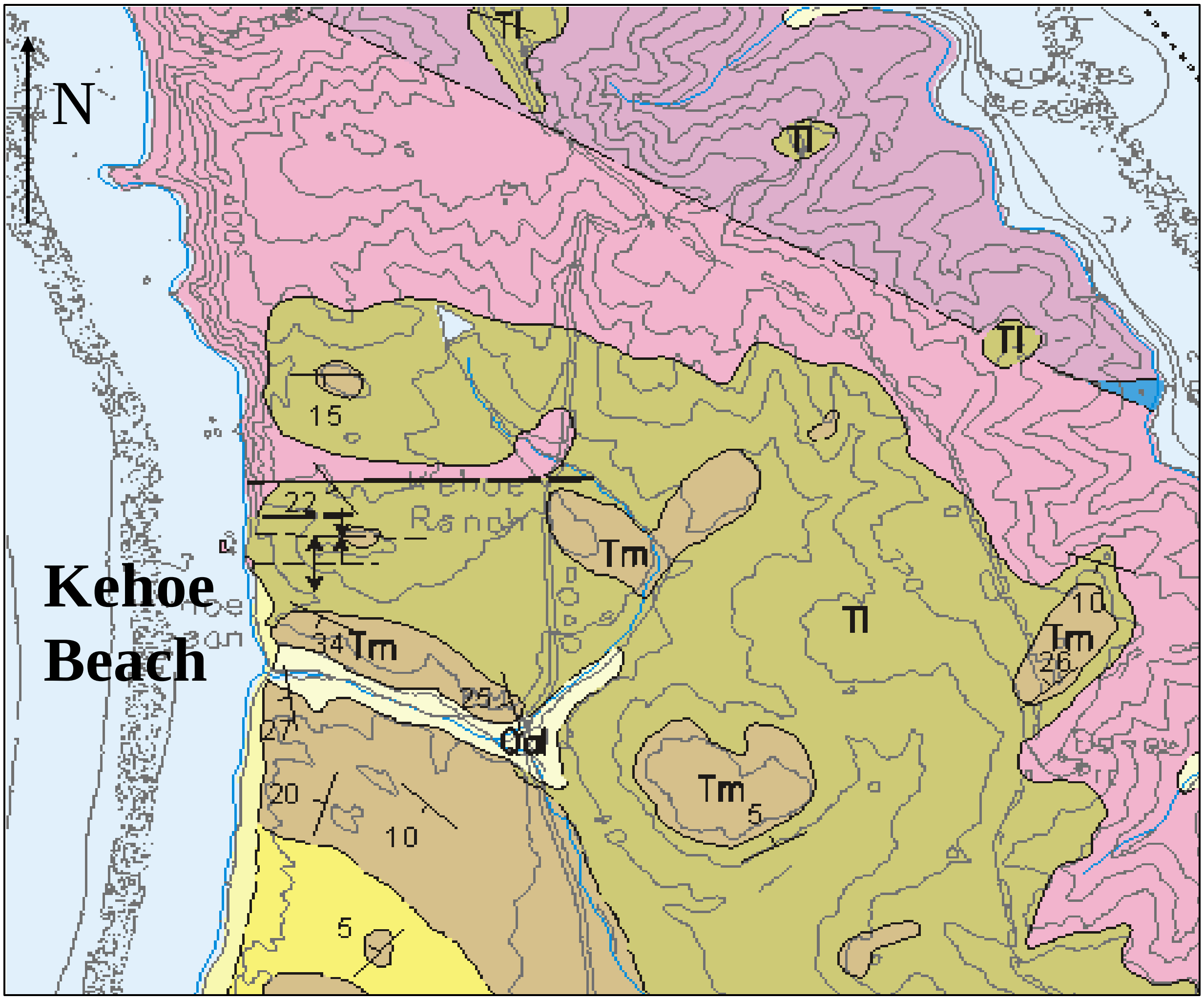
Monterey Formation -- Thin-bedded and laminated, light-colored porcelanite with very thinly laminated shale interbeds and few thin to medium interbeds of biotitic arkosic sandstone is as thick as 450 m on the southwest slope of Inverness Ride. Interbedded light-gray porcelanite, brown brittle chert, and dark-yellowish-brown mudstone with scattered dolomite concretions that form the upper part of the Monterey are estimated to be from 450 m to 900 m thick (Clark and others, 1984). The Lockhart well on Bolinas Mesa (well no. 6, Sheet 1) penetrated as much as 1500 m of the Monterey. This formation yields benthic foraminifers diagnostic of bathyal or greater depths and of Luisian and Mohnian (middle and late Miocene) age with most of the Monterey being Mohnian (Clark and others, 1984).

Santa Margarita Sandstone -- Massive, coarse - to fine-grained semifriable arkosic sandstone is commonly greenish where it contains 37 to 42 percent glauconite. In seacliff exposures near Double Point this sandstone is highly bioturbated and bituminous. At Santa Maria Beach a one-meter thick basal conglomerate contains abundant Monterey chert clasts, common greenish and black porphyritic siliceous volcanic clasts, and a few granitic pebbles. The Santa Margarita rests with angular unconformably on the Point Reyes Conglomerate of Galloway (1977) at Point Reyes and on the Monterey Formation east of Drakes Bay, where it varies from 5 m to as much as 60 m thick. The glauconitic sandstone has yielded a K-Ar date of 7.9 ± 0.3 Ma (Geochron Labs., 1997), which is late Miocene. Stratigraphic relationships to the under- and overlying formations also indicate that the Santa Margarita is late Miocene age.

Santa Cruz Mudstone -- Thin-to thick- bedded and faintly laminated olive-gray to pale-yellowish-brown siliceous mudstone contains thin elongate carbonate concretions. Silica content varies from 66.4 percent near Bolinas to 79.0 percent higher in the section (Clark and others, 1984, table 2). In the seacliffs southeast of Double Point, contains a few thin bituminous sandstone interbeds, whereas farther southeast bituminous sandstone dikes are locally common in the lower part of the mudstone section. As much as 1040 m of mudstone are exposed between Bolinas and Duxbury Points. With additional subsurface section, this formation may be as thick as 2000 m in the Bolinas Mesa area but thins to the northwest, where it pinches out east of Drakes Bay. A diatom flora from near Bolinas Point is assigned to the Nitzchia reinholdii zone of late Miocene age (John A. Barron, written commun., 1975, 1990). Calcareous benthic foraminifers are diagnostic of the Bolivina obliqua zone of late Miocene age (Clark and others, 1984, table 3).

Purisima Formation -- Thick- to very-thick bedded, light-olive-gray siltstone is locally diatomaceous and upon weathering becomes nodular and yellowish gray. Spheroidal carbonate concretions, elongate as much as 2 m, form prominent discontinuous interbeds and locally contain cetacean bones. Several thick interbeds of light-olive-gray, well-sorted, fine- to medium-grained lithic arkose appear bluish where fresh, are semifriable and commonly bioturbated. In the broad synclinal section at Drakes Bay, the Purisima is as much as 490 m thick. A diatom flora from the seacliff section at Drakes Beach is assigned to subzone b of the Nitzchia reinholdii zone of latest Miocene age (Zone X in Clark and others, 1984). The pinniped fauna is diagnostic of latest Miocene or Pliocene age (Repenning and Tedford, 1977). As much as 40 m of the Purisima at Drakes Bay is latest Miocene, but the upper part that is not as well dated is believed to range into the Pliocene (Clark and others, 1984).

Stop 5: Kehoe Beach



Qd	**Dune sands (Holocene)**	1 km
Tm	**Monterey Formation (middle to upper Miocene)** marine porcelanite and chert	
Tl	**Laird Sandstone (middle Miocene)** marine arkosic sandstone	
Kg	**Porphyritic granodiorite of Point Reyes (Upper Cretaceous)**	
Kqd	**Tonalite of Tomales Point (Upper Cretaceous)**	

Figure 17. Geologic map of Kehoe Beach (adapted from Clark and Brabb, 2000)

Lithology and Stratigraphy of Rocks Exposed at Kehoe Beach

Joseph C. Clark and Martin H. Link (from Bilodeau and Davis, 1990)

In the sea cliffs west of the Kehoe Ranch, granitic rocks of the Salinian basement are nonconformably overlain by a middle to upper Miocene sequence of sedimentary rocks. This sequence consists of a transgressive basal sandstone unit, the Laird Sandstone, and an overlying porcelanite unit, the Monterey Formation. The Laird Sandstone is faulted against the granitic basement to the north and folded along a syncline and an anticline to the south (Figure 17).

The oldest sedimentary sequence of the Point Reyes Peninsula, the Paleocene Point Reyes Conglomerate, is missing here, and the hiatus represented by the exposed nonconformity includes all of Paleogene time.

Salinian Basement

The Salinian block of the Point Reyes Peninsula consists of three lithologically distinct granitic facies: porphyritic granodiorite that is exposed at the Point Reyes promontory; granodiorite and granite that crop out along Inverness Ridge and are well exposed in the sea cliffs here; and hornblende-biotite tonalite that forms Tomales Point to the north. About 6 miles (10 km) north of Tomales Point at Bodega Head, lithologically similar hornblende-biotite tonalite exposures are the northernmost land outcrop of granitic rocks of the Salinian block west of the San Andreas fault.

The granodiorite and granite facies at Kehoe Beach is biotitic and along Inverness Ridge contains older metasedimentary inclusions and roof pendants of schist and gneiss, quartzite, calc-hornfels, and marble. Dikes and masses of aplite and alaskite are locally abundant. Radiometric dating indicates that these granitic rocks probably crystallized about 100 m.y. ago, during the Early Cretaceous.

Laird Sandstone

The Laird Sandstone is mainly of middle Miocene age. It reaches a maximum thickness of about 65 meters at Kehoe Beach, where it directly overlies granitic basement.

The Laird section at Kehoe Beach is the best exposed, thickest, and most fossiliferous on the Peninsula. One seacliff section was measured from the nonconformable contact with the granitic basement southward to the conformable contact with the overlying Monterey Formation. The Laird Sandstone thins to the east, where just west of Lairds Landing it is less than 12 m thick.

At Kehoe Beach, the base of the Laird contains a basal coarse-grained lag composed of weathered and partially cemented granitic basement debris. The lag is about 0.6 m thick and composed of boulders, pebbles, and sand-size particles of the underlying granitic basement. At one locality barnacle, mollusk (mostly Pectens and *Ostrea* sp.), small echinoid, and bryozoan fragments occur in this sandy, matrix-supported, basal conglomerate. This basal lag is interpreted to be weathered granitic basement that was reworked by shoreline processes as the sea transgressed over this area.

Overlying the basal lag is a sequence of alternating thick-bedded, medium- to fine-grained sandstones with minor beds of very coarse-grained sandy, granule conglomerate, and thin-bedded muddy and silty sandstones and mudstones. This sandstone is generally medium-grained, friable, light brown to light gray, and contains angular to subangular grains of quartz, feldspars, heavy minerals, and biotite that typically make up arkoses. Some of the individual beds are laterally continuous. Granitic pebbles occur in several of the horizons and delineate crude graded bedding and parallel and cross stratification. Several carbonate-cemented and concretionary zones occur within the section and are up to 3 feet (1 m) thick. *Thalassinoides* and other undefinable trace fossils occur in the middle and upper part of this section.

The Laird Sandstone has high porosity and permeability in the Kehoe Beach section and would make an excellent hydrocarbon reservoir. This formation has a wide aerial distribution and on the southwest slope of Inverness Ridge is locally bituminous, making it one of the key potential reservoir targets in the offshore Point Arena and Bodega basins.

Monterey Formation

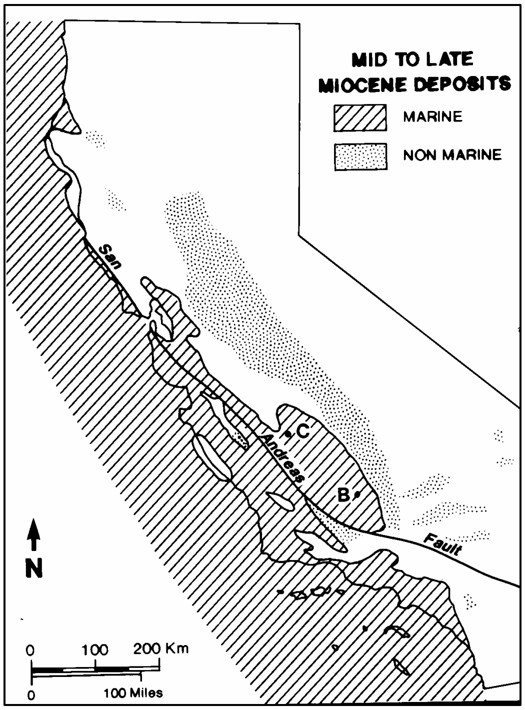
The upper part of the Laird Sandstone at Kehoe Beach is transitional into the Monterey Formation. At Kehoe Beach the Monterey Formation consists of alternating thin-bedded and laminated micaceous siltstone and pinkish-gray siliceous mudstones, porcelanites, and fine-grained sandstones. The sandstone beds range from less than 2 cm to 60 cm thick, are graded, and contain parallel and cross laminae and diatomaceous intraclasts. Abundant fish scales and fragments and external molds of calcareous foraminifers occur in these finer-grained strata.

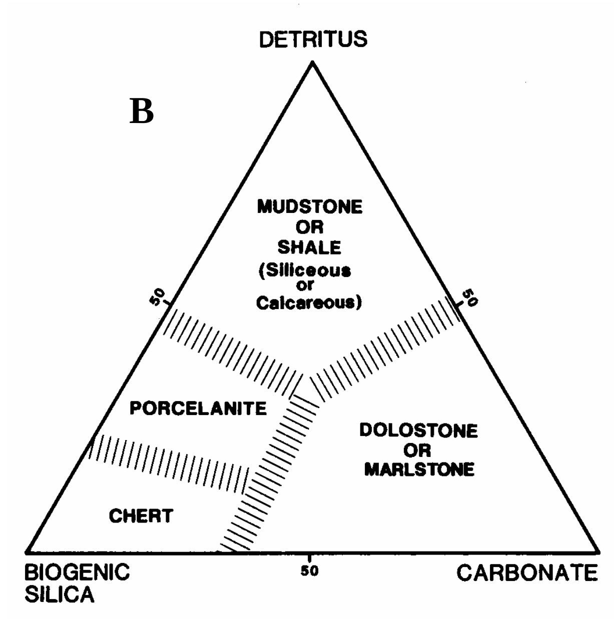
Although stratigraphically diagnostic fossils have not been recovered from the Monterey at Kehoe Beach, elsewhere on the Peninsula this formation yields benthic foraminifers diagnostic of a Luisian and Mohnian (middle and late Miocene) age with most of the Monterey being Mohnian (Clark and others, 1984). Only the lower part of the Monterey Formation is exposed here. Higher in the section the Monterey Formation becomes more siliceous and consists mainly of porcelanite and chert. The total thickness of the Monterey on the Point Reyes Peninsula is estimated by Clark and others (1984) to be on the order of 3,500 to 5,000 feet (1050 to 1500 m).

Depositional Environments of Laird Sandstone and Monterey Formation

The Laird Sandstone is interpreted to be a basal transgressive sandstone deposited in relatively shallow-marine waters. Much of its arkosic sediment is derived from the underlying granitic basement. The fragmented fossils and sedimentary structures indicate high-energy wave-related processes for the basal lag gravels, which were deposited in a rocky beach or wave-cut marine terrace setting. The discontinuous nature of some of the sandstone beds in the Laird suggests that the shallow-marine sands may have formed a narrow shoreline zone. The Laird fines upward, suggesting deposition in progressively deeper water as a result of the marine transgression. Quieter-water conditions followed in the middle and upper parts of the Laird, eventually deepening to bathyal depths in the Monterey. The overlying thin-bedded siltstones and graded sandstones in the transition zone between the Laird and Monterey formations are interpreted to be either: (1) more offshore shoreline or storm deposits interfingering with the shelf or slope fine-grained Monterey deposits; or (2) thin-bedded clastic turbidites interbedded with slope and (or) basinal Monterey Formation.

A





C

ROCK TYPE	POROSITY		PERMEA-BILITY
	CT	QTZ	
Mudstone (Siliceous)	20 - 30%	15 - 25%	< 1 md
Porcelanite	25 - 35%	10 - 25%	< 1 md
Chert	15 - 25%	2 - 15%	< 1 md
Dolostone	2 - 10%	2 - 10%	< 1 md

D

ROCK TYPE	FRACTURE SPACING (CM) (TABLE 2)	CALCULATED K FOR VARIOUS FRACTURE WIDTH			
		10 µ	15µ	20µ	30µ
Brecciated Chert **	0.3	56	187	445	1503
Chert *	2	4	14	33	112
Porcelanite *	4	2	7	17	56
Mudstone *	7	1	4	9	32
Dolostone *	9	1	3	7	25

** Cubic Model; * Matchstick Model

Figure 18.
A. Distribution of siliceous rocks of the Monterey Formation.

B. Definition of siliceous rock types in the Monterey formation. This applies opal CT and quartz rocks.

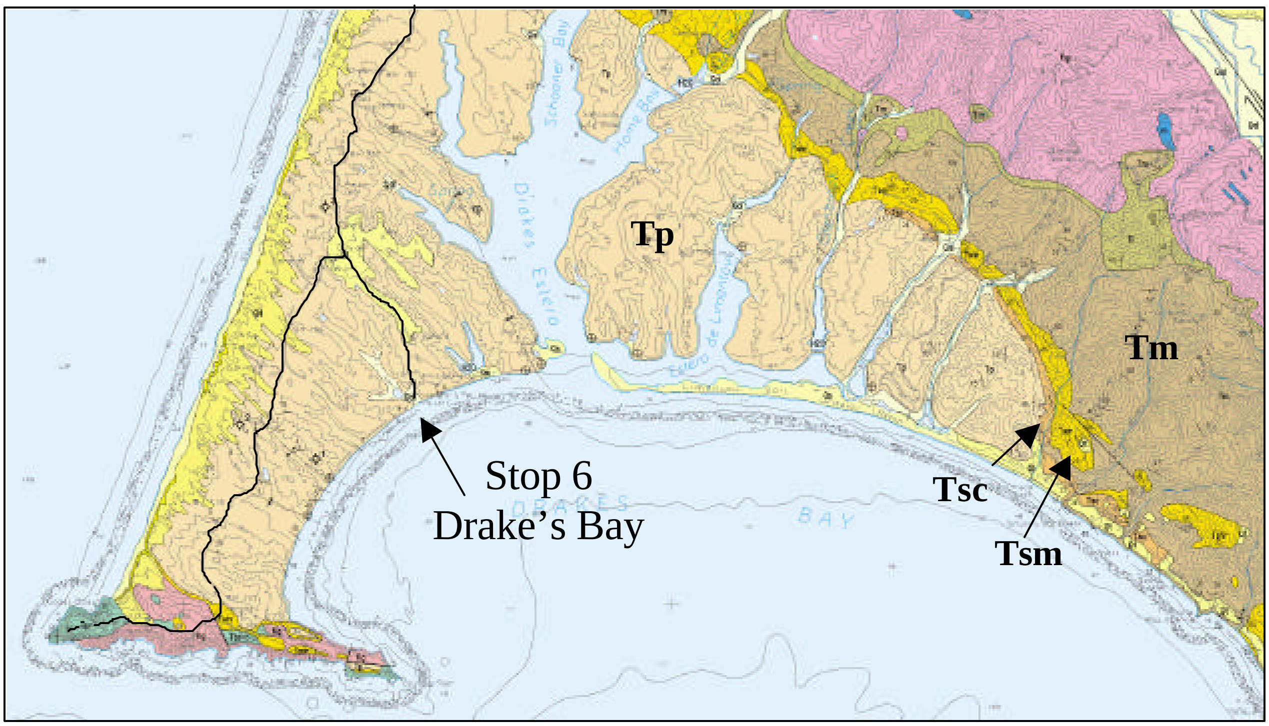
C. Range of porosity and permeability for siliceous rock types of the Monterey Formation in the Santa Barbara and Santa Maria areas.

D. Typical fracture spacing and fracture permeability for siliceous rocks in the Santa Barbara and Santa Maria area.

All diagrams from MacKinnon, 1989a & b.

Stop 6: Drakes Beach (edited from Bilodeau and Davis, 1990)

The rocks exposed in the cliffs at Drakes Beach are made up of diatomaceous mudstones and siltstones of the Purisima Formation. As you walk east along Drakes Beach you are approaching the axis of a broad syncline. Notice also how the strata dip toward the east but that the high-angle normal faulting is down to the west. Small caves form 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, sea stars, and other marine fossils in some of the sandier layers. The best viewing is far down the beach to the east. Remember, Point Reyes is administered as a National Park and rock collecting cannot be done without a permit. A fine example of a fossilized whale vertebra is on display at the Drakes Beach Visitor Center.



Tp = Purisima Fm.; Tsc = Santa Cruz Mudstone; Tsm = Santa Margarita Fm.; Tm = Monterey Fm.

Figure 19. Map shows location of the Drakes Beach Visitor center where we will see the Purisima Formation (adapted from Clark and Brabb, 2000)

LITHOLOGY AND STRATIGRAPHY OF ROCKS EXPOSED AT DRAKES BEACH

(in Bilodeau and Davis, 1990)

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Indiana, Pennsylvania 15705

A widely transgressive upper Miocene to Pliocene sedimentary sequence rests unconformably on all older rocks of the Point Reyes Peninsula. This sequence, which has a composite thickness of as much as 8,500 feet (2,550 m), consists of a basal glauconitic sandstone unit, the Santa Margarita Sandstone, a siliceous mudstone unit, the Santa Cruz Mudstone, and an upper siltstone, mudstone, and sandstone unit, the Purisima Formation. Clark and others (1984) applied these 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 fossil faunas and floras.

Purisima Formation

The Purisima exposed in the cliffs at Drakes Beach is typically a 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 replacement chert pods. Spheroidal carbonate concretions, elongate as much as 7 feet (2 m) parallel to the bedding, form prominent discontinuous interbeds and locally contain cetacean bones. Several thick interbeds of light-olive-gray, well-sorted, fine-to medium-grained sandstone are semifriable and commonly bioturbated. This 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 Point Reyes on the southwest and Inverness Ridge on the northeast, where this formation is as much as 1,600 feet (490 m) thick. Offshore seismic profiling (Clark and others, 1984) reveals that the synclinal Purisima section continues to the south above the granitic basement. In the offshore, south and west of the Point Reyes promontory, more than 1,835 feet (560 m) of Purisima is folded along a syncline and anticline, which in turn appears faulted against the granodiorite of Point Reyes to the east.

The Purisima of Drakes Bay has yielded a diverse fossil fauna and flora. Diatoms are locally common and occur with radiolaria and siliceous sponge spicules. Cetacean bones are common, whereas pinniped bones are rare and include the remains of a primitive fur seal and a walrus. Mollusks and echinoids are also rare.

Depositional Environment

The Purisima represents a shallow-marine phase of the upper Miocene to Pliocene sequence that began with transgression of the Santa Margarita Sandstone. This transgression was followed by basinal deepening with as much as 6,560 feet (2,000 m) of the Santa Cruz Mudstone deposited near Bolinas in the southern part of the Point Reyes Peninsula. With basinal filling, the Purisima was deposited in shallower water, largely at inner neritic depths, and locally transgressed the granitic basement to the northwest. Much of the Purisima subsequently has been eroded from the Point Reyes Peninsula, and throughout the Drakes Bay area the top of this formation has been removed.

Stop 7: Point Reyes Lighthouse (from MacKinnon and Schweller, unpublished guidebook, 2002)

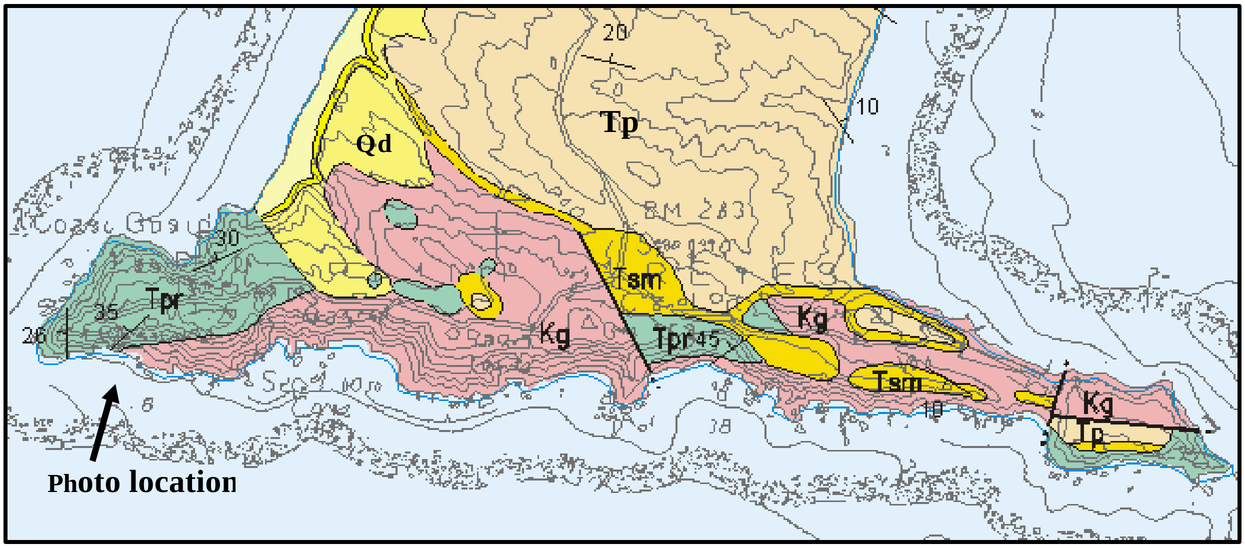
The Point Reyes lighthouse occupies the tip of the Point Reyes peninsula. The resistant tip of the Point Reyes peninsula is composed of granitic basement depositionally overlain by the early Eocene Point Reyes Conglomerate (Figure 20). The Point Reyes Conglomerate consists of both sandstone and conglomerate deposited as sediment gravity flows (turbidites and debris flows) in deep water. Although the extent of the outcrops is limited, they show the variable character and limited lateral extent of individual beds deposited in an extremely high-energy setting.

Well-known exposures of Late Cretaceous-Eocene turbidites occur at several localities along the California coast from Point Lobos northward. These include Point Lobos, Pigeon Point, Point San Pedro, Point Reyes, and the Gualala area (Figure 20). The outcrop at Point Reyes appears to be the same age as the lithologically similar Carmelo Formation at Point Lobos (Burnham, 1998). Along with other evidence, Clark et al. (1984) and Burnham (1998) have proposed that the Point Reyes conglomerate was once contiguous with the Carmelo Formation but was displaced northward 150 to 185 km along the San Gregorio fault during the Tertiary (Figure 20). Additional evidence for the displacement of the Santa Cruz mudstone, is given in Stanley and Lillis (2000).

The Carmelo Formation at Point Lobos, near Monterey to the south, is a well-known set of outcrops that is inferred to be a submarine canyon deposit. The evidence is compelling and includes the coarse nature of the sediments, limited lateral continuity of bedding, and the direct onlap of the sandstone and conglomerate against the inferred canyon walls, which are composed of granodiorite. Because of its similar lithological character and close association with granitic basement, the Point Reyes Conglomerate is also inferred to be a submarine canyon deposit.

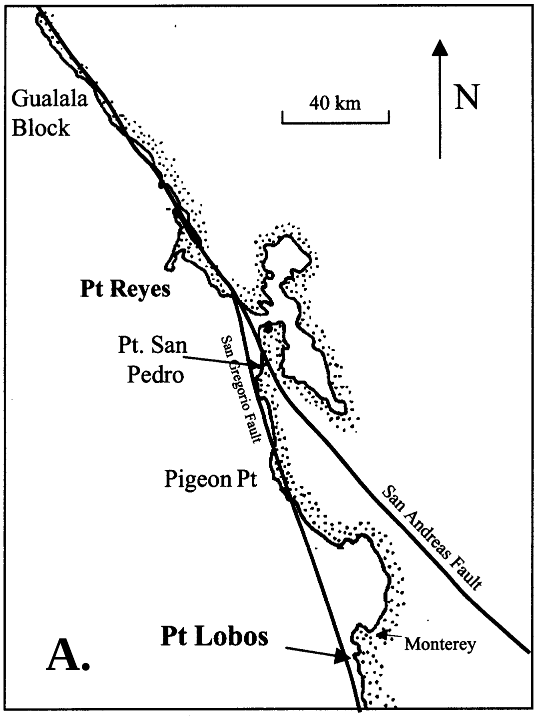
The granitic basement is part of the Salinian block, inferred to have once been part of the Sierra Nevada Batholith. Tectonic disruption and movement of the Salinian block towards its present location is believed to have begun prior to the Eocene with further disruption in the Late Tertiary. During the Late Cretaceous to Eocene times, the margin may have alternated between a subduction or transform regime. Regardless, voluminous turbidite deposition occurred offshore California at this time.

Submarine canyons are one of several main turbidite depositional systems that can serve as excellent hydrocarbon reservoirs. Submarine canyons have some very favorable attributes for hydrocarbon migration and entrapment. They are commonly filled with coarse sediment with excellent reservoir characteristics. Also, they are commonly situated along favorable migration pathways updip of potential fine-grained source rocks, and the canyon walls may serve as effective lateral seals. However, there are also many examples of submarine canyons that are filled with mudstone, and others that lack an effective updip seal.



Kg = granodiorite; Tpr = Pt Reyes conglomerate; Tsm = Santa Margarita Fm; Tp = Purisima Fm.; Qd = dunes

Figure 20. The photo shows the visitor's center for the Pt Reyes lighthouse. The lighthouse is to the left of the photo and much closer to the waterline. Note the contact between the Pt Reyes conglomerate on the left and the granitic rocks on the right; part of the contact is drawn in where it seems most obvious. On top, the contact can be located to within a few feet, but we have yet to find an accessible location where you can put your finger on it. Map from Clark and Brabb (2000). Photo from web site: http://www.californiacoastline.org/cgi-bin/lookupform.cgi.



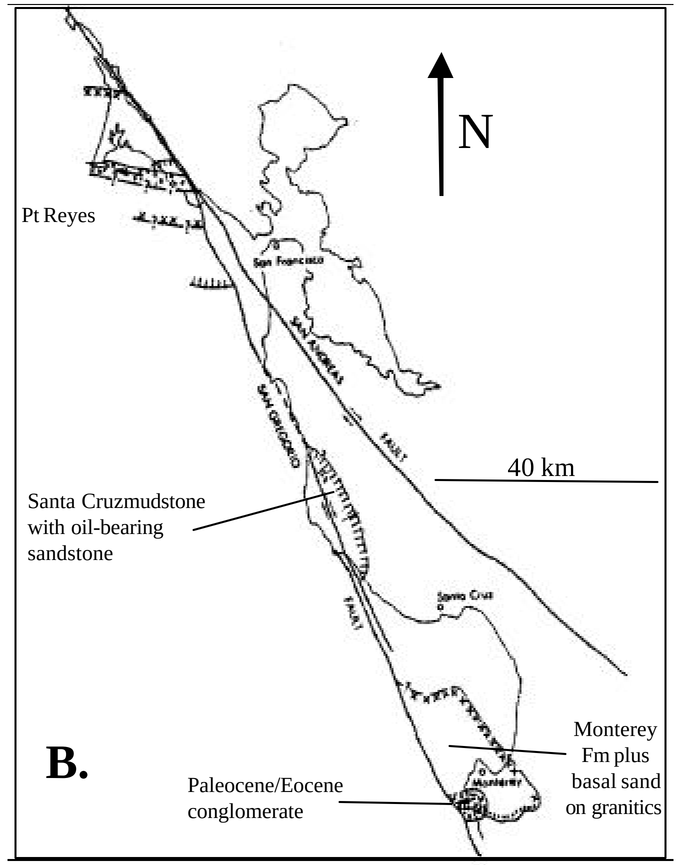


Figure 21. A. Location of non-Franciscan, Late Cretaceous to Eocene turbidites outcropping along part of the California coast. B. Location of strata thought to have been displaced from the Monterey and Santa Cruz area along the San Gregorio fault. Inferred initial movement of the Monterey area strata is ~11 to 12 m.y.a. Santa Cruz mudstone was deposited ~ 7 to 9 m.y.a. and therefore was not displaced as far. Map B adapted from Clark et al (1984) with additional data from Stanley and Lillis (2000).

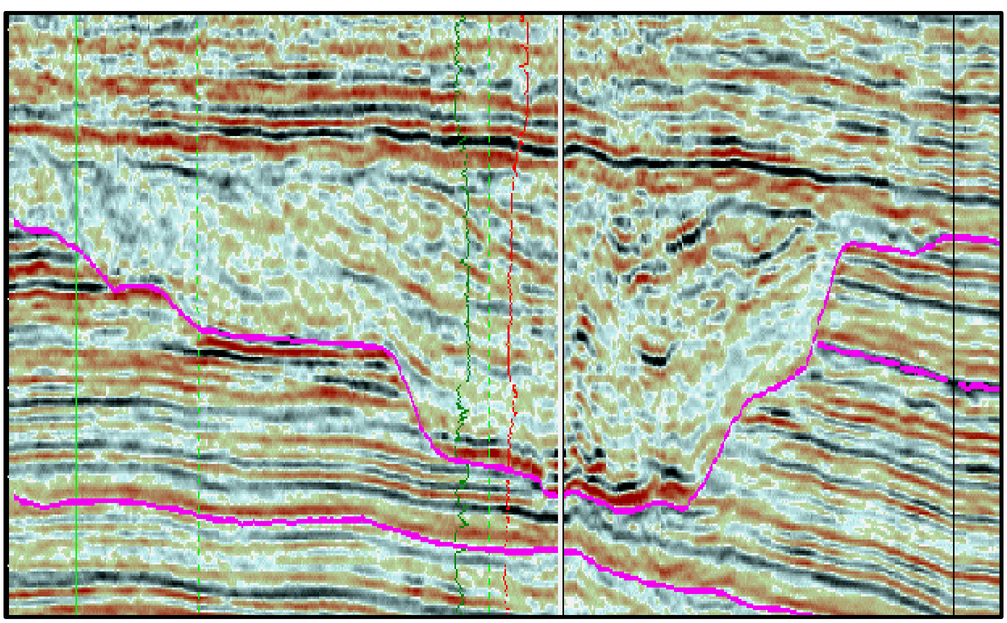


Figure 22. A typical example of a submarine canyon seen on seismic; location unknown.

OFFSHORE GEOLOGY AND EXPLORATION HISTORY OF THE BODEGA BASIN & NEARBY AREAS

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Point Reyes has been the site of petroleum exploration since the late 1800s. Early exploration geologists were attracted to an oil seep in the Monterey Formation near the town of Bolinas. However, since the 1960's the offshore is thought to have the most petroleum potential. The prospective section is Tertiary marine sediments, which were deposited on granitic basement and are exposed at field trip stops 5 and 7.

Offshore Basins

The Bodega Basin lies offshore, west of the Point Reyes Peninsula. The basin is approximately 70 miles in length, extending as far north as the town of Gualala, California (Figure 23). 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 the Point Reyes Peninsula (Figure 15) expose Tertiary sediments and Mesozoic bedrock. These rocks represent the stratigraphy of the southeastern portion of the Bodega Basin. Outcropping Tertiary rocks include siliceous shales of the Monterey Formation and pre-Monterey sandstones, which are potential reservoir targets offshore.

The Cretaceous granitic basement present beneath Bodega Basin affects the structural style of the sediments deposited on it (Hoskins and Griffiths, 1971). Both the P-039-1 and P-041-1 wells penetrated granitic rock at total depth (Zieglar and Cassell, 1978). Granitic rock was also encountered in some of the onshore wells (Figures 15 and 23). Offshore structures underlain by granitic rock are generally broad, low amplitude folds, in contrast to other basins having tightly folded structures and floored by Franciscan basement.

The Santa Cruz Basin is located south of Bodega Basin and Point Reyes (Figure 23). The basin is bounded on the west by the Santa Cruz High and on the east by the San Gregorio Fault having primarily strike-slip movement. Coastal outcrops in the Santa Cruz Basin can be found just west of the San Gregorio Fault. These rocks may reflect the stratigraphy found in the offshore Santa Cruz and Bodega basins, 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 Point High anticlinorium. The Outer and possibly Inner Santa Cruz basin likely have Franciscan and not granitic basement.

Previous Offshore Exploration Activity and Results

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 from 1963 to 1967 Shell Oil drilled ten exploratory wells including sidetracks in Bodega Basin and two wells in the Outer Santa Cruz Basin (see Figure 23). All twelve wells were drilled in water depths ranging from 200 feet (61 m) to 440 feet (134 m) and were plugged and abandoned. The locations of the wells are plotted on Figure 23. The map shows that the majority of the exploratory wells were drilled along anticlinal axes. According to Hoskins and Griffiths (1971), many of the wells tested major structures. Normal mud weights were used and no significant drilling hazards were encountered (Zieglar and Cassell, 1978). Since that time, no other exploratory drilling has taken place. The results of all the wells drilled on P-1 leases were made available to the public in December 1974 (Zieglar and Cassell, 1978).

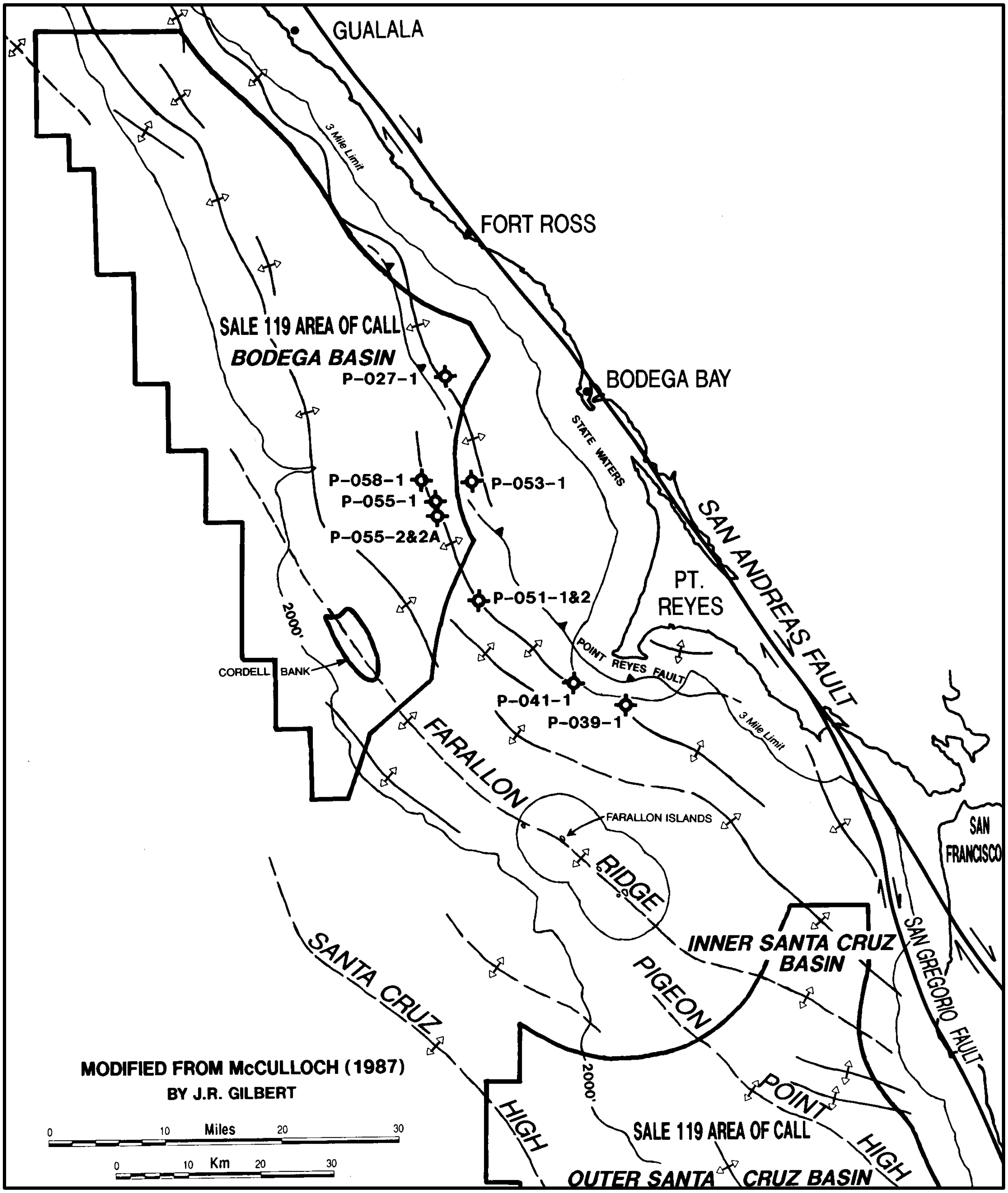

Figure 23. Regional tectonic map of coastal and offshore northern California (after McCulloch, 1987). Sale 119 Area of Call was a nomination area in the 1980's.

The pre-Monterey sandstone in Bodega Basin may be the most attractive exploration target. The sandstones are stratigraphic equivalents to the Miocene Laird Sandstone that crop out on the Point Reyes Peninsula (see Stop 5) and to the Paleocene to Eocene age German Rancho Formation near Gualala. These potential reservoir sandstones lie beneath the siliceous shales of the Monterey Formation and have oil shows in many of the offshore wells. The only drill-stem test conducted in Bodega Basin was in lower Miocene sandstones at the P-027-1 well from 1470 to 1520 feet (Minerals Management Service, 1983). A fluid rise of 1300 feet occurred inside the tubing but only drilling fluid, mud filtrate, and water were recovered.

The Miocene Monterey Formation is also an attractive reservoir target (see Stop 5). The Monterey consists of siliceous and cherty shales that crop out on the Point Reyes Peninsula and occur offshore in Bodega Basin. The rocks are naturally fractured and occasionally have tarry oil. Farther south in the offshore Santa Maria Basin and Santa Barbara Channel, siliceous Monterey shales serve as both an oil source and reservoir rock. Claystone and shale overlie the Monterey Formation in the Bodega Basin and are stratigraphically equivalent to the Santa Cruz Mudstone and Purisima Formation and crop out on the Point Reyes Peninsula. These sediments may help serve as a hydrocarbon seals for Monterey and pre-Monterey reservoirs.

Lease Sale Status

During the 1980's, several Federal OCS lease sales involving Bodega, Santa Cruz and other California basins were rescheduled and eventually canceled. For example, OCS Lease Sale No. 119 originally scheduled for March 1991, included the Bodega and Santa Cruz Basins but was cancelled. The Area of Call for Nominations (Figure 23) was only in federal waters and represented the largest possible area that could have been offered for leasing. It included lease blocks ranging from approximately 6 to 45 miles offshore from Sonoma, Marin, San Francisco, San Mateo, Santa Cruz, and Monterey Counties. The Area of Call did not include sensitive wildlife areas and marine waters near Point Reyes, the Farallon Islands, and Cordell Bank. Cordell Bank was designated a marine sanctuary in May, 1989 and covers approximately 400 acres. In December, 1989 another ruling was passed prohibiting oil and gas leasing and drilling within the marine sanctuary. Marine water up to three miles from the coastline is governed by the state. State waters along the northern, central, and much of the southern California coast have already been assigned ocean sanctuary status, which prohibits any oil and gas leasing and drilling.

President George Bush Sr. in 1989 assembled a special task force to advise him on energy and environmental needs prior to any final determination on future offshore leasing in northern and southern California plus southern Florida. In January 1990, the task force delivered its report to the President. Shortly afterwards, the president disclosed there would be no future leasing in federal waters in these areas.

General Procedures for Offshore Leasing and Drilling

When an offshore lease sale is held, oil companies competitively bid against each other for each lease in a sealed bid process. A domestic or U.S. lease block typically covers nine square miles. The company bidding the highest bonus acquires the lease. Bonus is the cost paid in U.S. dollars for acquiring each lease. The Minerals Management Service, an agency of the Department of the Interior, is responsible for ensuring that the government receives fair market value for the leases receiving bids and has been known to reject bids that are considered too low. The minimum bid for a lease in the 1980's was $144,000 or $25.00/acre but the winning bid was typically much more. The most expensive offshore California lease was acquired by Chevron

USA during Sale No. 53 in May, 1981 for $333,596,200. The bonus, along with a yearly rental fee, is paid to the federal government. Most leases expire in five years but in some frontier basins and deep-water areas lease terms may be as longer. A company can hold a lease beyond its primary term by drilling a successful exploration well that finds significant hydrocarbons and then submits a plan for development.

During the lease term, the operating oil company may drill an expendable exploratory well on their lease after applying for and receiving the necessary federal, state and local permits. An Exploration Plan has to be submitted and in California it has to be approved by the California Coastal Commission. The Exploration Plan is the anticipated plan of action for exploratory drilling on a lease. Since an exploratory well can cost an oil company approximately 10 to 20 million U.S. dollars, usually only a few exploratory wells are drilled in a basin following a lease sale. The well locations are decided by oil company personnel after many man-years of work evaluating expensive subsurface data such as seismic collected in the area. Strict environmental procedures must also be followed. When exploratory wells are eventually drilled, a comprehensive down hole evaluation program is done to determine the potential of the area for accumulating hydrocarbons. The wells are then plugged with cement and abandoned. If the well did not encounter and test oil or gas in potentially commercial quantities, it may be decided that no additional exploratory wells will be drilled on the lease. However, if the drilling proved successful and there was a discovery, a follow-up exploration well would likely be drilled to help determine the size of the accumulation. If the reserves are considered to be large enough from the additional exploratory drilling and the project is estimated to meet economic thresholds, then plans can be made to develop the field at a much larger expense to the company.

Additional federal, state and local permits also have to be acquired before proceeding with field development. Eventually a platform may be built, transported and installed over the field. When the platform is in place, numerous development wells are drilled to encounter and produce the oil and gas trapped in the subsurface. The oil and/or gas is then transported from the platform to shore normally by a pipeline through federal and state waters or it may be offloaded onto a barge that stores the oil until other vessels arrive to transport it to refineries. It may take five to ten years after a lease sale is held before the first hydrocarbons are ever produced and transported to market. At the end of a field's productive life, the wells are plugged with cement and the metal casing is cut below the mudline, plus any platform(s) are removed and dismantled.

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