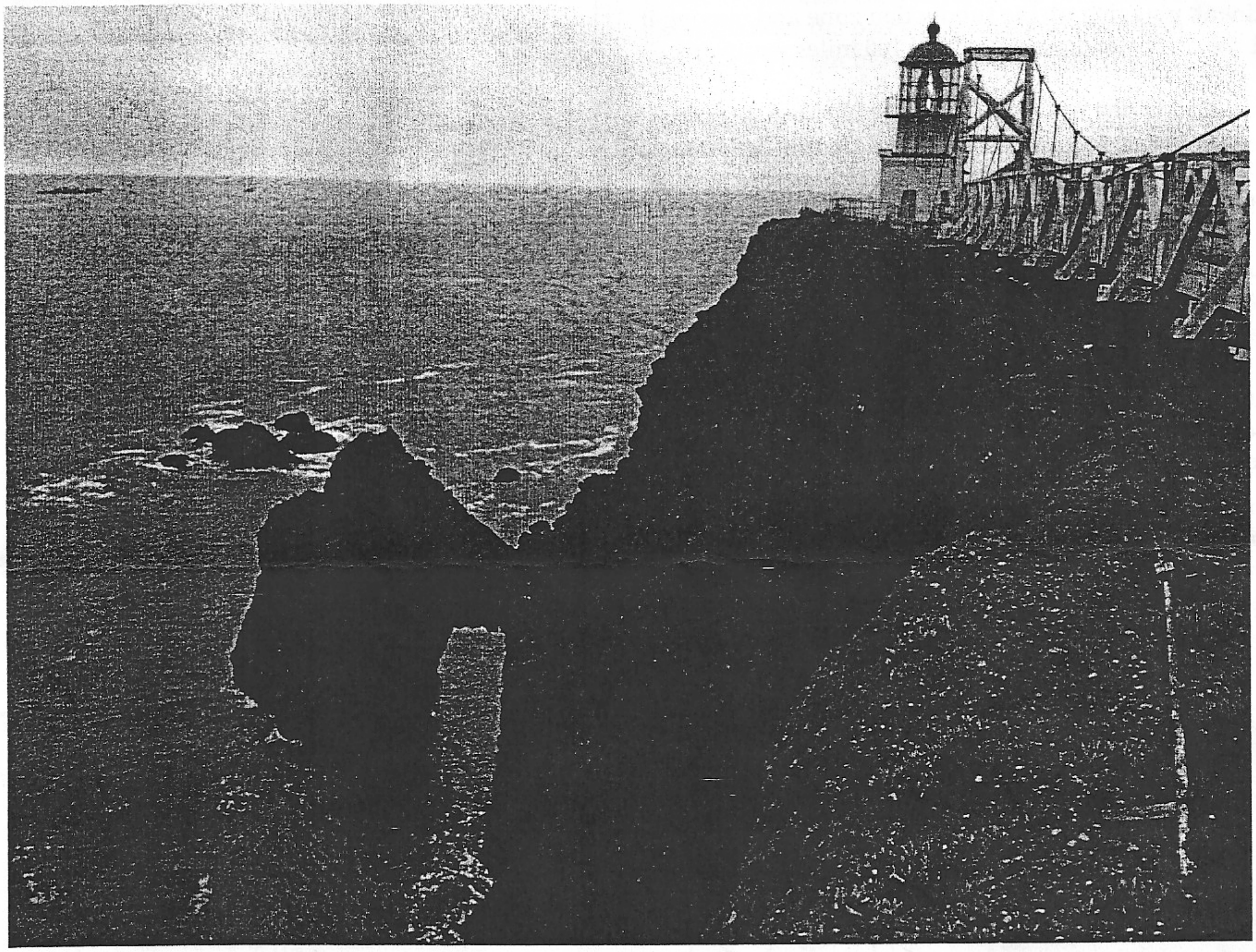
Written in Stone: Lessons from the Field for the Earth Science Classroom

Marin Headlands Field Trip March 10, 2011
National Science Teacher's Association Annual Meeting 2011 San Francisco



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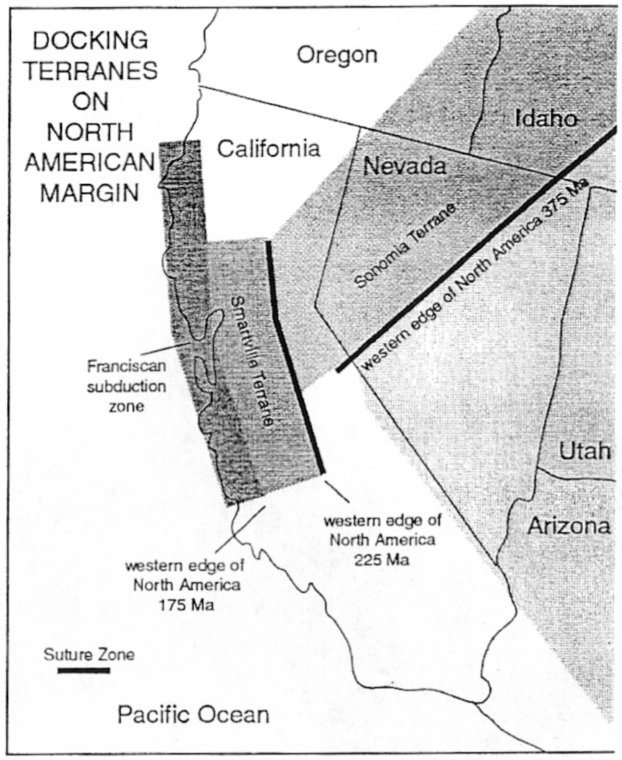
California Geology - Franciscan Assemblage

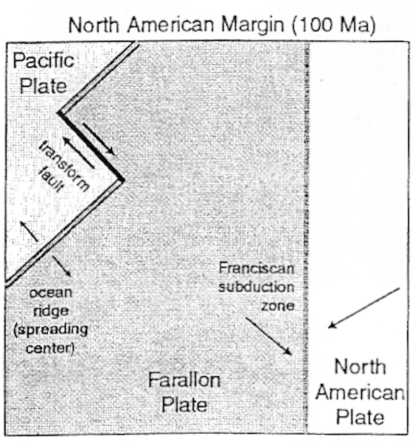


About 375 Ma (million years ago), the western edge of the North American plate cut through the center of modern-day Nevada. The continental margin was a subduction zone. The lower portion of the subducting plate descended into the mantle and was assimilated. The upper portion, however, was scraped off in slivers and accreted. For 150 m.y., the Sonomia terranes accreted to the North American continent, plugging up the subduction zone and moving it (and the continental margin) about 100 miles westward.

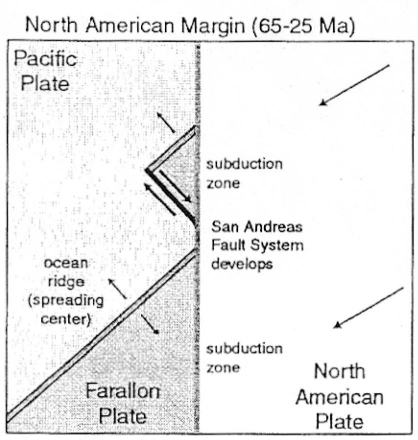
About 225 Ma, the western edge of the North American plate was near the present-day Sierra foothills. For 50 m.y., the Smartville terranes accreted, again plugging up the subduction zone and moving it further west.

Around 175 Ma, the Franciscan subduction zone formed, and for 110 m.y., the Franciscan Assemblage terranes accreted along the North American continental margin.

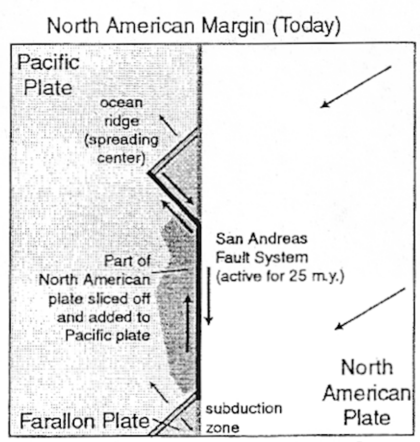
During the Franciscan accretion, tens of thousands of feet of rocks accumulated in the subduction zone and accreted to the continent in successive near-vertical slivers that extended up to 30 miles below the surface. Continental sediments moved into the offshore trench and were themselves caught up in the accretion process. By 65 Ma, much of the Farallon plate was entirely subducted: the North American plate was now overrunning the spreading center that separated it from the Pacific Plate. The plate boundary began changing to a transform plate boundary between the Pacific and the North American plates.



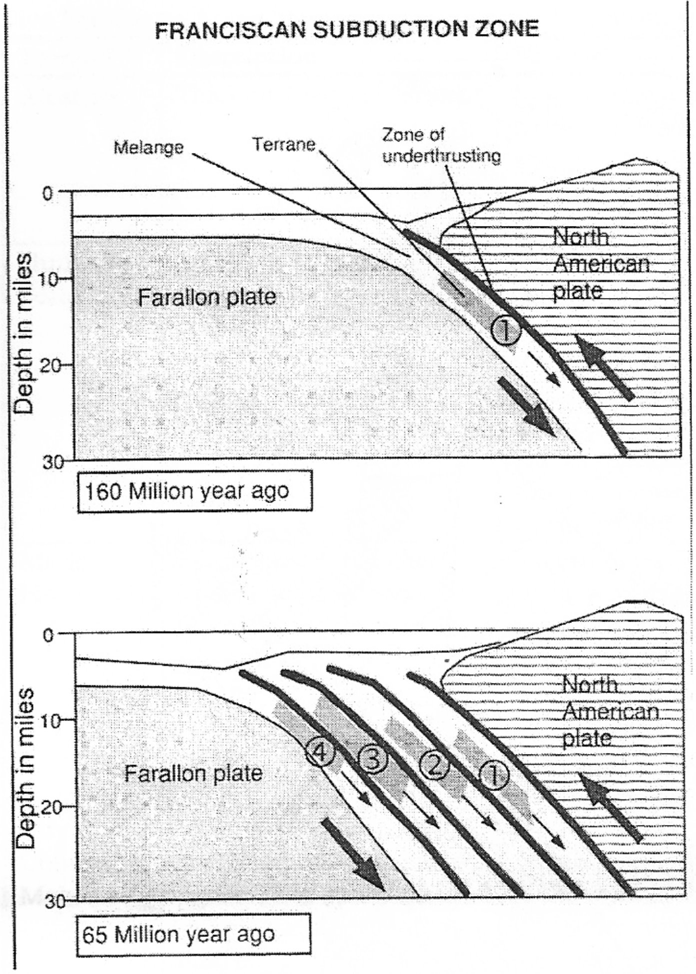
The Farallon plate moves east into the Franciscan subduction zone. (Active from 175 to 65 Ma.) Franciscan Assemblage begins forming. The East Pacific Rise spreading center was also moving east toward the subduction zone.

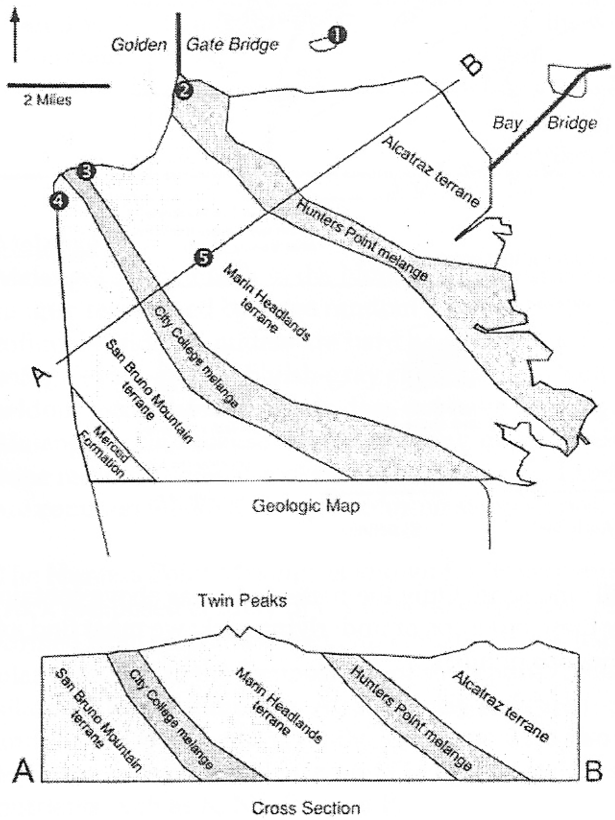


The East Pacific Rise spreading center reached the Franciscan subduction zone. Subduction stopped where the Pacific plate entered the subduction zone because the Pacific plate was moving away from the subduction zone. Part of the Pacific plate began to be carried under the North American plate.



Part of the North American plate attached to the Pacific plate and began to move northwest. The San Andreas fault formed and became the boundary between the Pacific and North American plate. The west edge of the fault moves north with the Pacific plate at about 2 in/yr relative to the rest of North America.





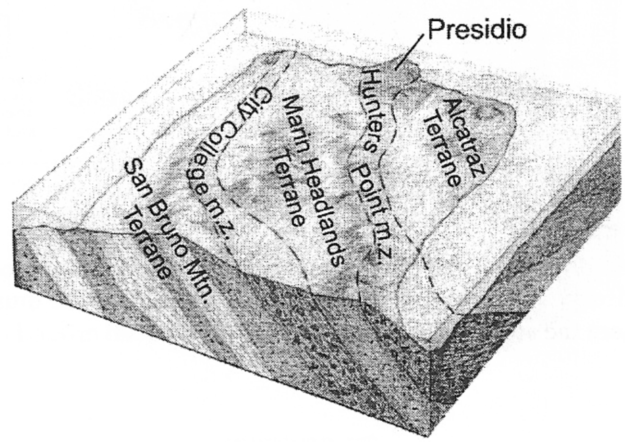
The Franciscan rocks in San Francisco consist of five distinctly different terranes that accreted one after the other. As the Farallon plate subducted under North America, it would periodically either get scraped off or stuck and broken off. That portion of the subducting plate would then become part of the North American plate (accretion). The subduction zone would move westward and begin subducting under the newly accreted margin of North America. In such a manner, each terrane was progressively shoved under the preceding one, and the North American margin moved westward.

The boundaries between terranes are called shear zones; they display textures and mineralogy associated with the results of severe shearing as one terrane was thrust against another.

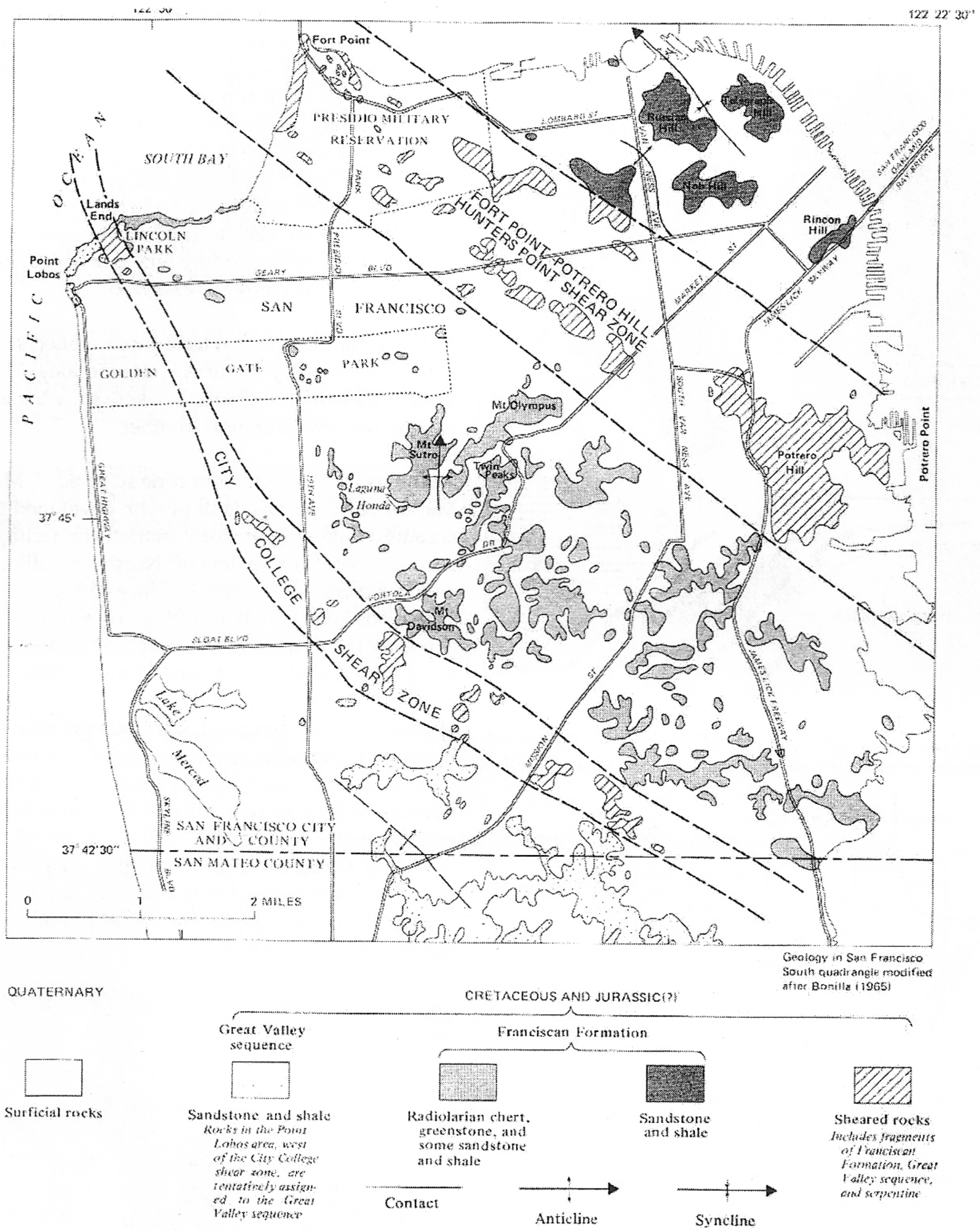
The Franciscan subduction zone stopped 65 Ma. 25 Ma, the San Andreas Fault System developed to accommodate the transform motion connecting the seafloor spreading centers off Northern California and in the Gulf of California. Since 65 Ma, the region has been slowly uplifting and eroding, exposing the Franciscan rocks at the surface. Now we see the top edges of these terranes (slivers that still extend to great depths below us). These edges appear as parallel stripes that run diagonally northwest across the city.

Because of their accretion order, the slivers further inland are the oldest; the ones closer to the plate boundary are the youngest. (Imagine a stack of pancakes tilted parallel to the angle of the subducting oceanic plate. The oldest pancake – first one accreted – is on top!)

Figures from 1998, T. Konigsmark, *Geologic Trips: San Francisco and the Bay Area.*



(Figure courtesy of Golden Gate National Recreation Area.)



Note that most of San Francisco is covered by surface soils, landfill, and sand. Only the patterned areas above contain bedrock. To see into the Franciscan Assemblage, we must look for these outcrops of underlying rock; we must find areas where the surface sediment deposits have been eroded (usually the tops of hills).

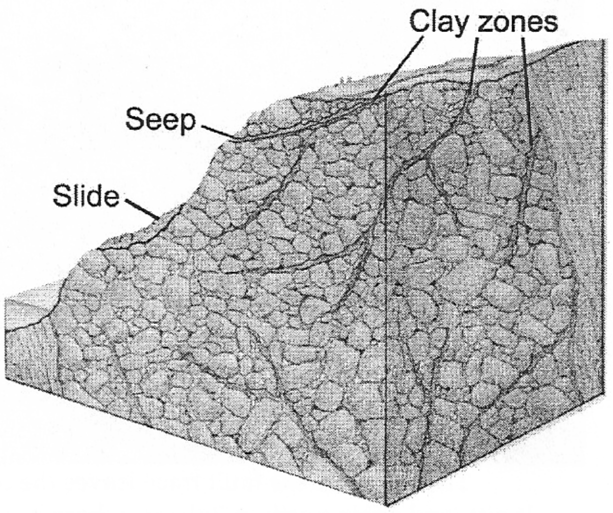
Five Franciscan Assemblage terranes that you find around San Francisco (listed in order from oldest to youngest):

Terrane	Description	History
Alcatraz	Thick-bedded sandstone	Grains were derived from many different rock types eroded along the North American continental margin and carried by rivers to the ocean and into the trench by turbidity currents (avalanches of sediment) down submarine canyons (deeply carved features that extend off the continental shelf). Transportation, deposition rapid.
Hunters Point	Melange: large blocks of serpentinite in soft clay and serpentine matrix.	Formed along the zone of thrusting between the rocks of the Marin Headlands terrane and the Alcatraz terrane, while those rocks were in the subduction zone. Serpentinite forms at a spreading center where mantle rocks are altered by hot seawater that reaches the deep rocks through cracks formed during spreading. (Serpentinite forms the lower part of the earth's oceanic crust worldwide.) Small isolated blocks represent pieces of oceanic crust that were broken up and squeezed upward through the overlying host rock like watermelon seeds.
Marin Headlands	Pillow basalt, red chert, shale, and sandstone, typically in thin fault slices.	Record of the 100 m.y. migration of mid Mesozoic Pacific Ocean floor from its eruption, close to the equator, on a spreading ridge, to its accretion by subduction thousands of km to the northeast. Pillow basalt overlain by ribbon chert (hardened silica-shelled muds, formed when planktonic silica-shelled organisms die, and their shells slowly rain down to the ocean floor (1 cm/1000 yr) and collect over time), overlain by turbidity-current-transported sandstone of continental origin, deposited just prior to accretion.
City College Melange	Melange: blocks of basalt, chert, serpentinite, schist, gabbro, and sandstone in soft clay and serpentine matrix.	Formed along the zone of thrusting between the rocks of the San Bruno Mountain terrane and the Marin Headlands terrane, while those rocks were in the subduction zone. The rocks are thoroughly ground up by thrusting. Blocks in the melange are pieces of hard rock that survived grinding.
San Bruno Mountain	Sandstone	Grains were derived from many different rock types eroded along the North American continental margin and carried by rivers to the ocean and into the trench by turbidity currents (avalanches of sediment) down submarine canyons (deeply carved features that extend off the continental shelf). Sand and seafloor mud in layeRs.

Melanges

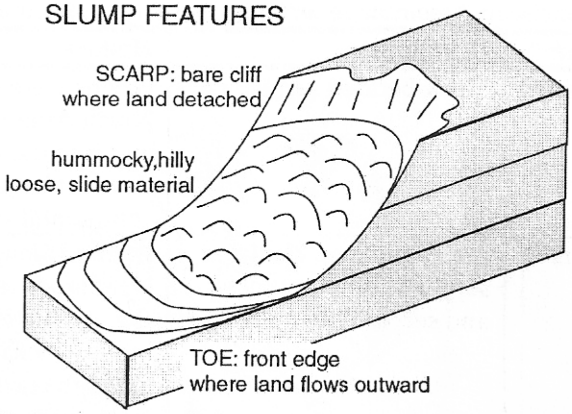
Melanges are common in the Northern California coast ranges: recognized by large random boulders sitting on rolling hillsides. Boulders are hard and stand out from the soft greenish-gray or bluish-gray clay matrix, which is seldom seen. The clay matrix does not have layering. Melanges form because intense shearing in the subduction zone reduces the hard rocks to a sheared paste. Landslides are common where melanges occur on steep slopes.

The Hunters Point Melange is known for its serpentinite. (rock composed entirely of the mineral serpentine). Soils formed from serpentine are characterized by anomalous plant life, due to the composition of serpentine: Fe and Mg silicate. There is almost no Al, so no clay soils are formed, and the soil is thin and gravelly. The serpentine also has toxic amounts of Mg, Ni, Cr, and Co, and is low in plant nutrients such as K, Na, Ca, and P.



SERPENTINITE:
Figure courtesy of Golden Gate National Recreation Area.

Most common plants avoid serpentinite, but a few hard and specialized plants thrive under these conditions: including Tiburon Indian Paintbrush, Oakland Star Tulip, and the very rare Tiburon Mariposa Lily (~2 ft high and blooms in May and June with cinnamon and yellow flowers).



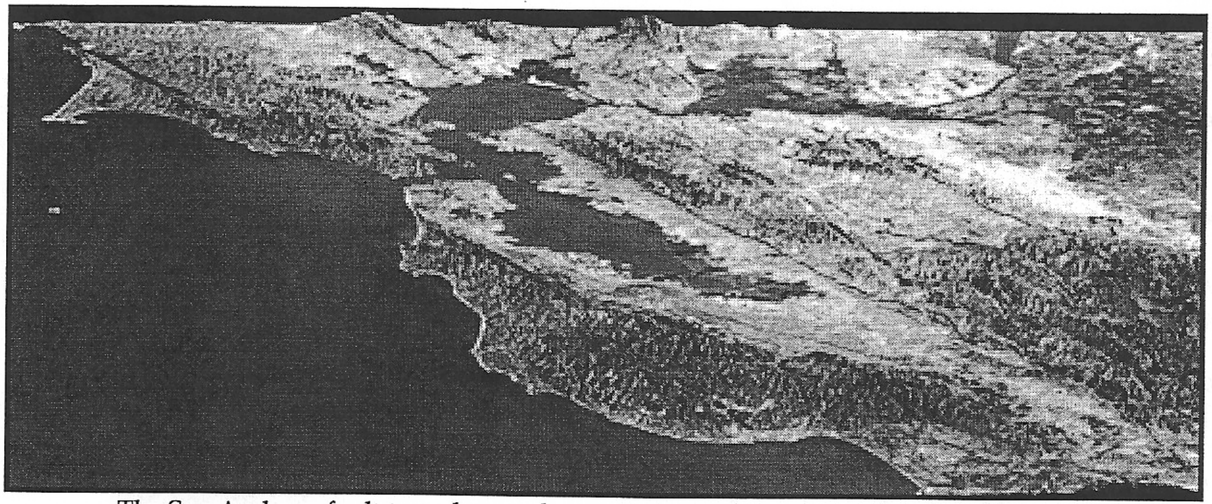
On fresh exposures, the rock is pale green, sometimes with dark specks about the size of small peas. These dark specks are remnants of pyroxene crystals that have been altered to serpentine. In places, some large blocks of this serpentinite have broken off and are slowly sliding down hillsides, lubricated by the soft and slippery clay of the underlying mélange. Rainwater accumulates in fractures in the serpentinite and makes its way down to the contact with the clay. Putting water along this contact zone is like putting wax on the bottoms of skis. The fine clay matrix holds water near the surface and is quite slippery when wet. The clay flows downhill, taking roads, buildings, and whatever else has been built on the melange.

Many homeowners think that if they build their homes on solid rocks, they'll have little chance of a landslide. But the solid rocks in mélanges are really just boulders surrounded by a clay matrix. And if the boulder is serpentinite, it will hydrolyze quickly and get weak when in contact with surface water.

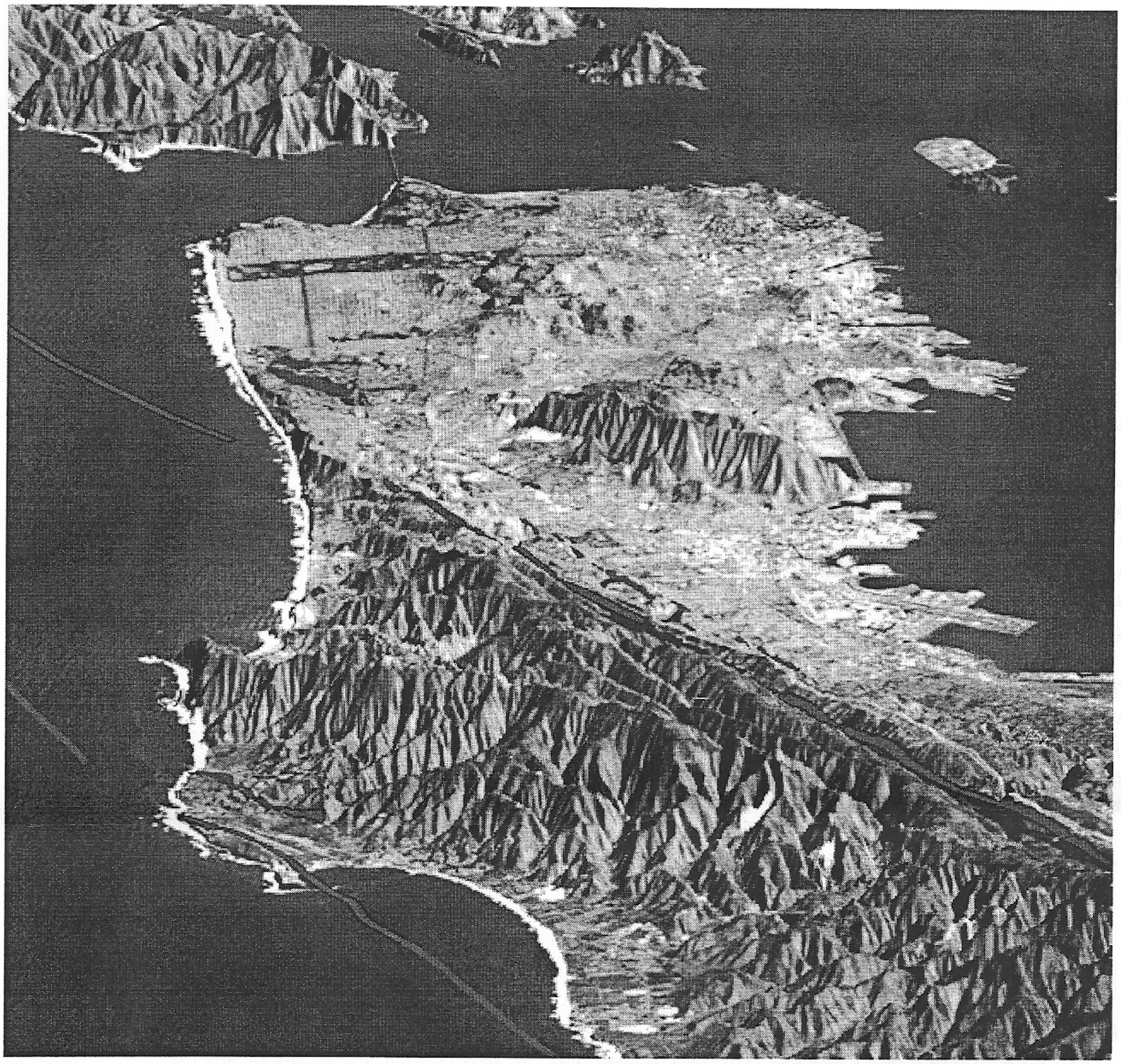
About 65 Ma, the tectonics of the California coastline between Northern California and Baja California began a radical change. Prior to that date, it was a convergent plate boundary, with an active subduction zone. But about 65 Ma, the subduction zone plugged up with sediment from the accretionary wedge and the subduction of an active spreading center. Over the next 35-40 m.y., a transform fault boundary arose. This new plate boundary developed into the San Andreas fault system (SAFS) about 25 Ma. turbidities

Recent history

Once the subduction zone disappeared, the coastal rocks began to uplift, because there was no longer a force pulling downward into a subduction zone. The crust pushing upward created an early version of the coastal mountain chain. For the past 5 m.y., while uplift has occurred along the California coast ranges, the area around San Francisco Bay has been an anomaly - subsiding and letting the Pacific Ocean flood into the Sacramento River to form San Francisco Bay. The tops of some of the older hills became islands, such as Alcatraz and Angel Island.



The San Andreas fault trace leaves the coast at Mussel Rock south of Fort Funston.
It hits land again north in Bolinas, where it cuts across Point Reyes and then goes back to sea.



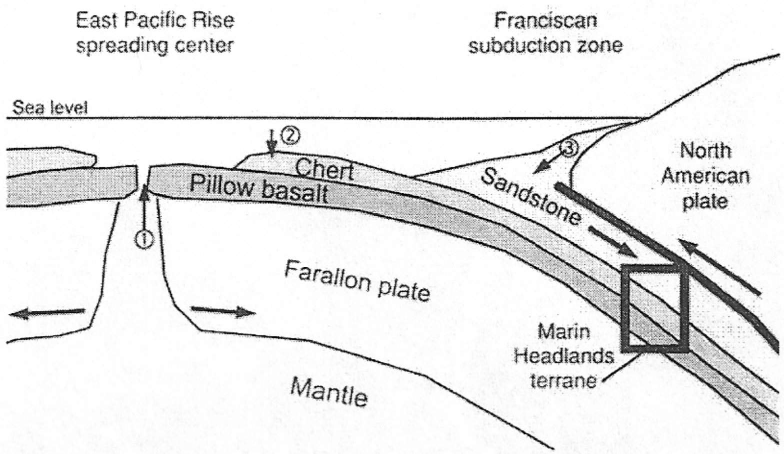
Notice that the region around San Francisco Bay is uplifting (mountainous),
while the Bay itself is subsiding.

Marin Headlands Terrane Details

MARIN HEADLANDS TERRANE DISCUSSION

The Marin Headlands terrane is the upper portion of oceanic crust. It consists of pillow basalt, red ribbon chert interlayered with shale, and sandstone. These rocks were once part of the ocean floor of the Farallon plate. Around 100 Ma, they were crammed into the subduction zone and broken into numerous thin fault slices, so now they lay scattered around the Marin Headlands in pieces.

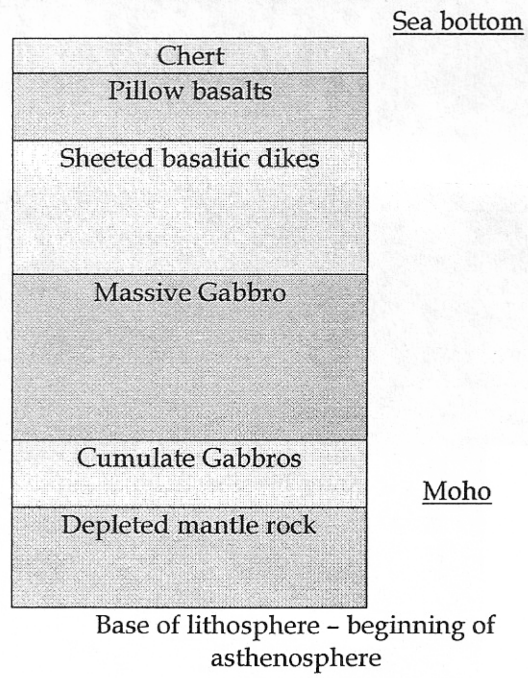
ORIGIN
Marin Headlands Terrane



Ophiolites

Ophiolites are pieces of ocean crust that were trapped in convergent plate boundaries and accreted to continental crust. Ophiolites are rare and unique opportunities to study ocean crust without having to drill or dive. We are lucky to have some good samples along the western margin of North America. The Marin Headlands terrane is part of an *ophiolite* sequence, containing only the top three layers of ocean crust. (See following stratigraphy.)

OPHIOLITE STRATIGRAPHY



Review of how ocean crust forms

1. Deep mantle rock melts due to drop in pressure under spreading centers. Melts remove certain elements preferentially from the mantle rock, leaving behind depleted mantle rock.
2. Melts migrate upwards and accumulate in magma chambers. Over time, the magmas cool. They form minerals that drop to the bottom of the magma chamber becoming cumulate gabbros.
3. As new magma enters the magma chamber, the pre-existing magma is pushed upward to erupt. It breaks through the surrounding rock, forming dikes (conduits for the magma to move upward).
4. The erupted material becomes pillow basalt. The dikes eventually crystallize, and new ones form.

CHERTS

Cherts form from the lithification of silicic muds (oozes) that cover the basalts. Silicic muds form through the continual accumulation of microscopic glass shells of oceanic plankton (radiolarians). These shells rain down slowly through the open ocean when the plankton die. In addition, some of the silica in these muds is precipitated directly from saturated ocean water. They form only far from shore, where no land-derived sediments can cover them up. These muds accumulate slowly over time, and so get progressively thicker away from the spreading center (over older rocks).

The layered chert of the Marin Headlands contains interlayered beds of shale (which come from fine mineral dust from the atmosphere that fell into the ocean and accumulated in the silicic muds). The silicic and mud layers segregated themselves after burial. Folds in the beds come from slumping of still soft chert and later deformation in the subduction zone.

The Marin Headland chert comprises one of the largest historical sections represented in a single chert sequence in the world. The chert is full of radiolarian shells, which you can see with a hand lens and which record pelagic deposition well below 4500 meters over a period of 100 m.y. The shells are made entirely of silica. Radiolaria are single-celled organisms that evolve very quickly, geologically speaking. A particular species can show up in the fossil record and become extinct within a few million years. Since radiolarians spread quickly throughout the world's oceans, a particular species shows up in the fossil record at the same time worldwide, making radiolarians excellent index fossils. If you know the age of a rock with a particular radiolarian species, you know the age of any rock that contains that species anywhere in the world. Radiolarians are among the first organisms to show up in the fossil record. Radiolarians still live today, drifting in the ocean currents, new species appearing and some species becoming extinct. Their shells are still falling to the ocean floors, forming new ribbon cherts.

In the 1980s, geologist Bonnie Murchey (of the U.S. Geological Survey) solved the riddle of the Marin Headlands chert formations. She found a spot in the Headlands that had a complete thickness of chert (about 80 meters), and she meticulously removed the tiny radiolarians from all of the layers. She identified all the radiolarian species, and then compared each layer with rocks with known ages in other parts of the world. As a result of her work, we now know the ages of many of the Marin Headlands rocks.

At Battery 129, you can see red ribbon chert – thinly banded and layered with soft red shale. Red chert fractures into sharp tabular plates a few inches across. You can see much folding and layering. Shale fractures into thin layers, millimeters thick. These layers were deposited over 100 Ma on the deep ocean floor. We can see them now thanks to their accretion in the Franciscan subduction zone over 100 Ma. That means the lowest rocks in the section are about 200 Ma!

Point Bonita Lighthouse
Pillow basalt forms when basaltic magmas erupt under water, like in rift valleys in seafloor spreading centers. The water surrounds the lava, giving it a bulbous shape and quickly cooling the outside layer to glass. (Liquids that are quickly quenched turn into glass; there are no crystals, no minerals.) Molten lava inside the pillow breaks a small hole in the newly formed bulb and pushes out another bulb. Through this process, the lava creates an ever-growing cauliflower-like pile of pillows. (The crystal size of pillow basalts tends to increase inward, because the centers cooled slowest.) Pillow basalts are usually immediately weathered and altered on the ridge where they formed (altered by percolating hydrothermal solutions, like you see today at deep-sea vents). Such low-grade metamorphosis changes the basalt minerals to others, mostly chlorite, which gives the rocks a green color, and a metamorphic name of **greenstone**.

At Point Bonita Lighthouse, you can see **pillow basalt** in many different states of weathering and metamorphosis. Colors range from dark green on fresh surfaces to red, brown, or yellow where weathered. The first samples we will see, however, are some of the best-preserved formations found anywhere. These pillow basalts originally formed underwater at a seafloor spreading center. You can see them now on land thanks to their accretion in the Franciscan subduction zone. Observe the pillow basalt from the east side of the bridge and close-up from the west side. Notice the gouged-out edges – the waves can more easily weather the edges of a pillow basalt than the centers. This differential weathering results from the brittleness and fragility of the glassy rinds versus the hard, resistant crystalline centers. In the walk back to the car, watch as the pillows get progressively more and more weathered. We will stop at one sample, so you can observe a pillow up close.

Rodeo Beach – North
Turbidites are sandstones that formed from deposits of turbidity currents. Turbidity currents are underwater avalanches of sediment that shoot down submarine canyons. The currents are heavy in sediment and when they reach the bottom of the canyons, they drop their load quickly (heavy material first, with

the lighter material slowly settling out of the water atop the heavier material). We call this sorting **graded bedding**, and all turbidites display it.

The turbidite sandstones of the Marin Headlands are hard to find, because they so easily weather (though fossil Ammonites have been found in the unit). Those sandstones that are visible are difficult to identify, because of the extreme weathering. The north and south cliffs on Rodeo Beach provide sample outcrops. Go to north edge of beach and look at the sandstone cliff face.

Rodeo Beach - Sand

Sand is moved along beaches by longshore transport, a process whereby incoming refracted waves hit the shore with a component of push in one direction. This push picks up sand and water and moves it that direction. For North American this push is usually to the south (since most storms happen to the north, generating waves that move to the south).

Sand originates from a few different sources: local biological debris (like coral reefs), local rocks eroding (headlands and cliffs), or eroded material brought from the backcountry via rivers and distributed southwards by longshore transport (for North American beaches). Sand is ultimately removed from beaches and the longshore transport system through two primary methods: wind blows it onshore where it is buried and turned into sandstone or an offshore submarine canyon pulls the beach sand offshore, ultimately leaving it at the base of the canyon in a fan on the continental rise.

Here at Rodeo Beach, the sand is all locally derived, hence the large grain size and the chert and basalt composition. Two rare minerals can be found in this beach sand: jade (light green) and carnelian (bright orange form of chert).

Rodeo Beach - South

Along the southern portion of Rodeo Beach, you can see chert and basalt, intermingled with turbidite sandstones and younger beach and landslide deposits. Walk close to the cliff wall and observe the rocks. There is even an interesting exposure of green chert and red chert - caused by differences in the oxidation state of small amounts of iron in the chert.

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Geology of the Golden Gate Headlands

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