The geologic evolution of Point Lobos

The rocks at Point Lobos originated far away, under very different conditions from those that prevail here today. Their origin and translocation involves the interaction of great plates of the earth's crust. Plate tectonics, the term commonly used to describe the effects of this interaction, derives from heat variations within the earth's mantle (perhaps as a result of different concentrations of radioactive minerals). These variations are thought to drive huge convection cells within the mantle (Fig. 1). Upward-rising mantle creates large cracks in the earth's lithosphere, *oceanic ridges*, that are sites of volcanism and new crust formation (Figs. 1 and 2). The new crust moves away from the oceanic ridge and forms a plate that extends across the ocean floor until it encounters another plate (Fig. 3). The oceanic ridges are major features of the earth's surface and can span entire oceans (Fig. 4). The ridges are broken by large fractures in the crust called *transform faults* (Fig. 4), across which the ridges step sideways and newly created crust moves laterally (Fig. 5).
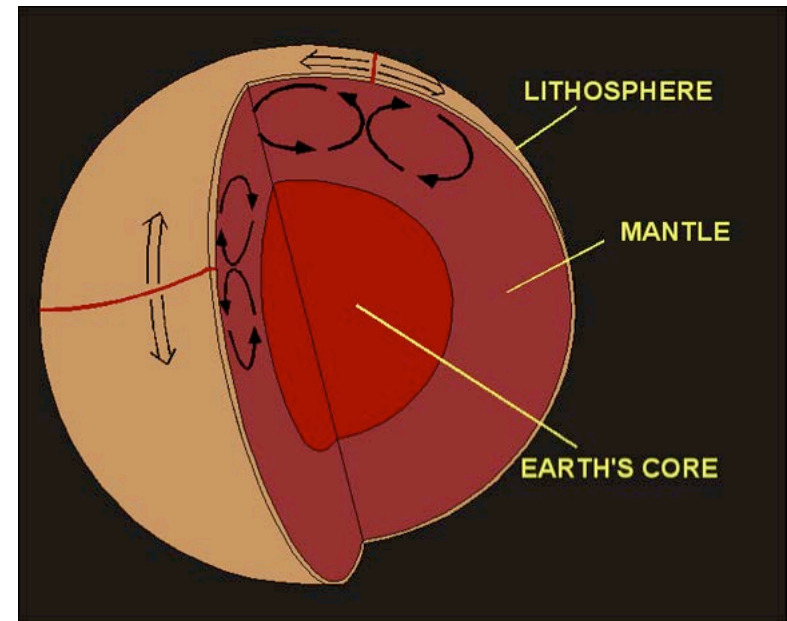

Figure 1. Cross section of the earth showing the nickel-iron core, the extremely dense plastic mantle and the rigid outer shell (lithosphere). Convection cells in the mantle cause the lithosphere to crack and spread apart.

Figure 2. Cross-section of the outer part of the earth where mantle material wells up in a crack on the earth's surface. The cracks occur predominantly in the ocean and form extensive oceanic ridges. Newly formed crust spreads away from the crack, giving rise to the term "sea-floor spreading".
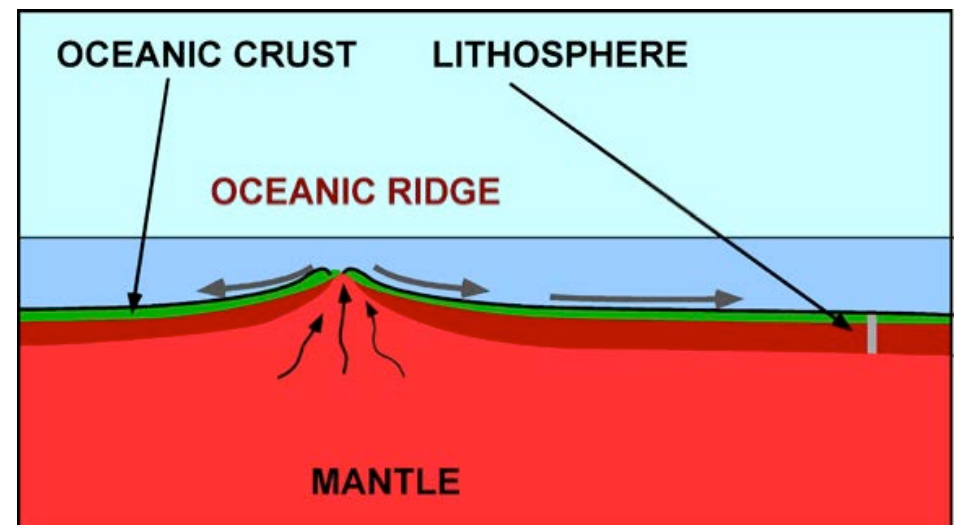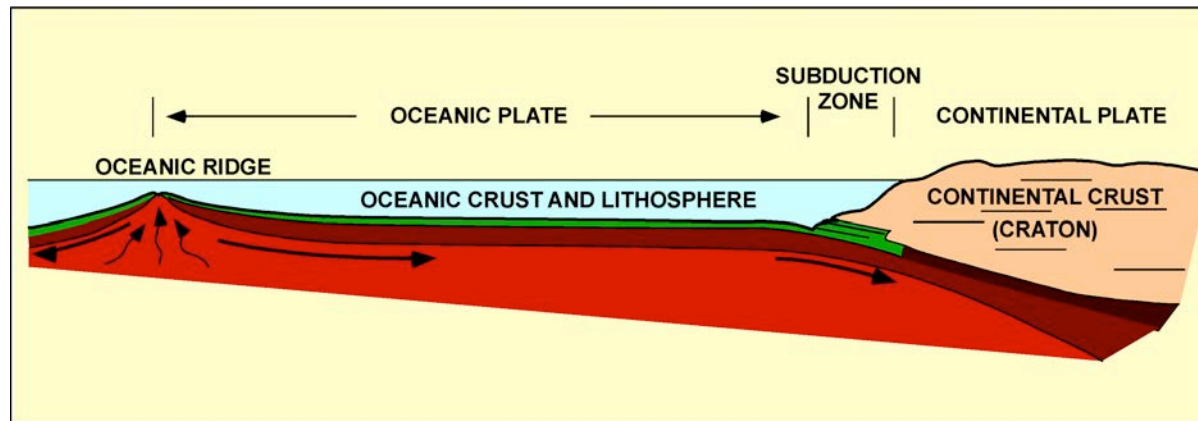
Figure 3. Idealized oceanic plate extending from an oceanic ridge to an adjacent continental plate.
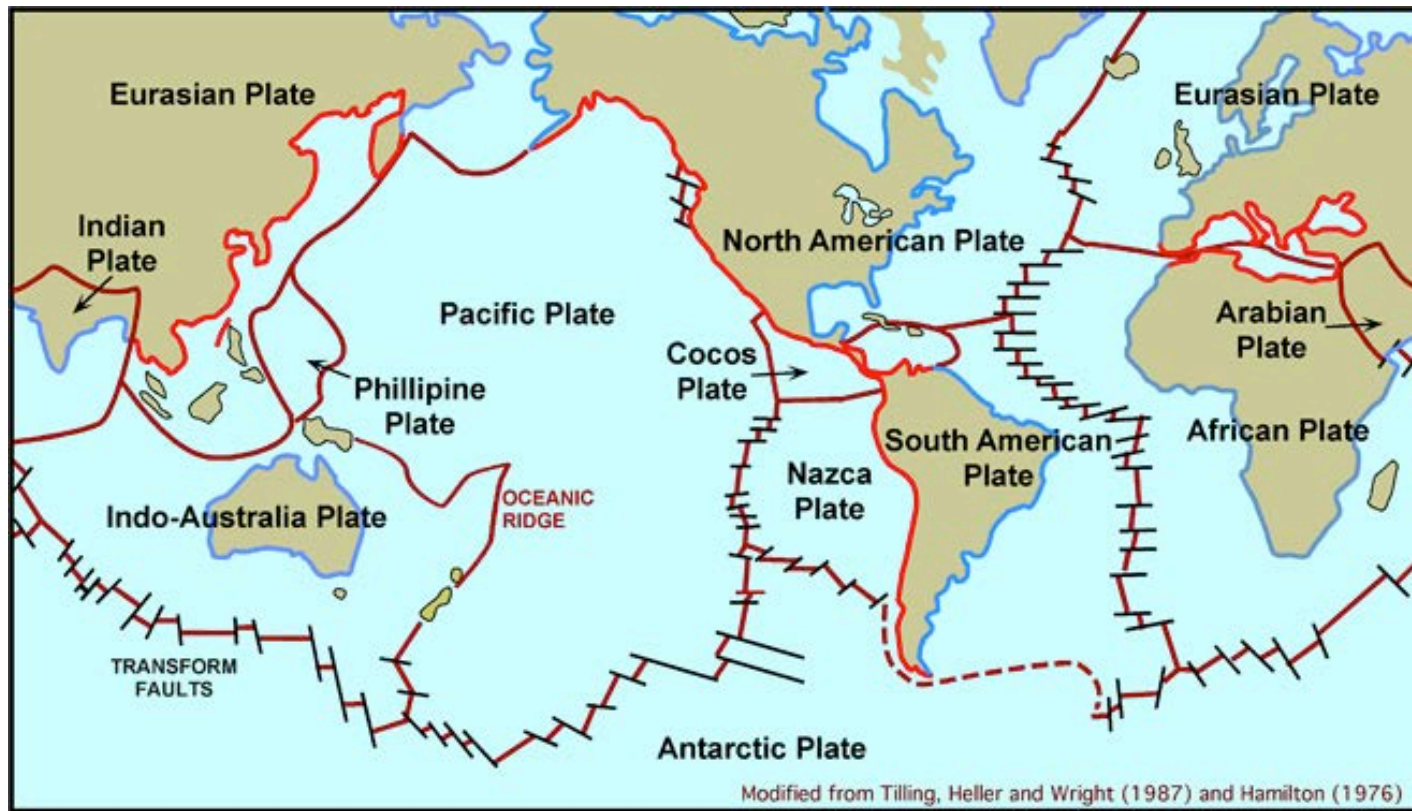

Figure 4. Major lithospheric plates of the world. Inactive (passive) continental margins shown in blue; active margins in red. The rocks on active margins are young relative to the age of the earth and on which earthquakes and volcanoes are common. Modified from Tilling, Heller and Wright (1987) and Hamilton (1976).
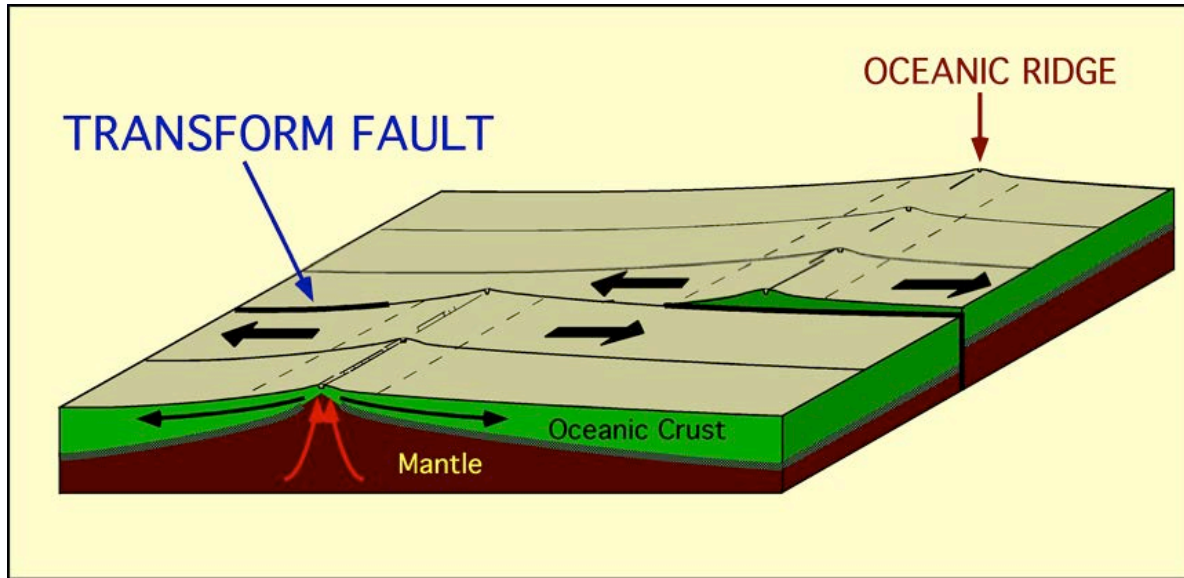
Figure 5. "Transform faults" are giant fractures in the earth's crust, across which an oceanic ridge is displaced. Offset of the ridge is not necessarily ongoing, but the crust on opposite sides of the fracture may be moving in opposite directions or in the same direction, but at different rates and elevations.

Figure 6. Oceanic crust, composed of heavier elements, differs significantly in thickness from continental crust, which consists of less dense minerals. Part of the reason for this difference in thickness is that oceanic crust is continually being formed and destroyed.
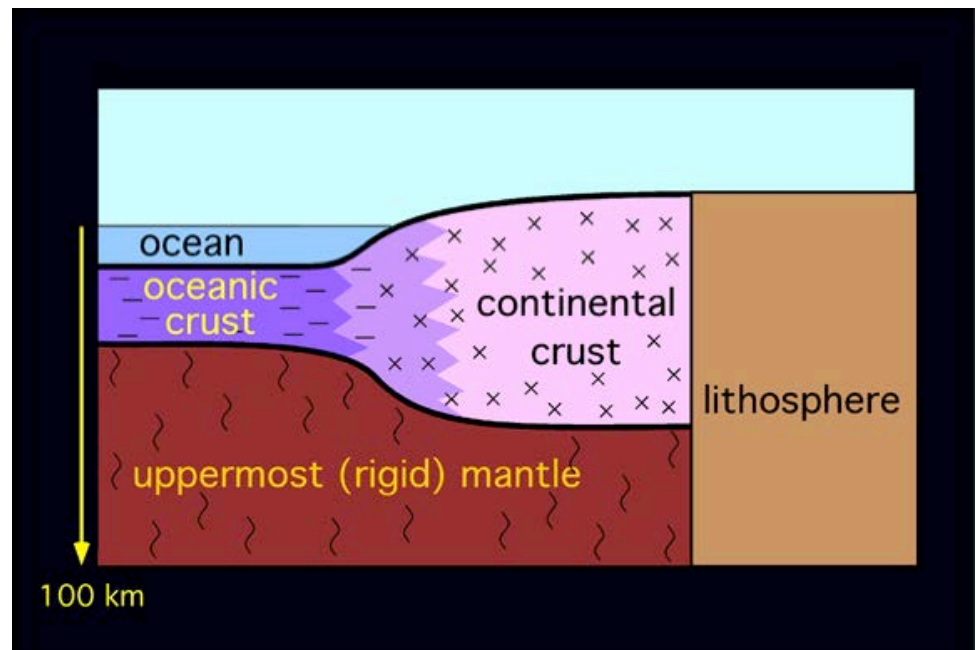
The geologic history at a continent's margin depends greatly its position relative to a plate boundary (Fig. 4). Many continental margins, such as those on the east side of North and South America, most of Africa and all of Australia lie well within a plate. Such margins are geologically "quiet" sites of sediment accumulation. Other continental margins coincide with the boundary between crustal plates. Rock here is continually being created and destroyed. Earthquakes and volcanoes are common features. The geologic history on an active margin is further controlled by the nature of the interaction. Where the boundary between the plates parallels the transform faults, the plates slide sideways relative to each other. Such a margin is called a "transform margin" (Fig. 7)

Where the plates collide head-on a different process occurs. If the other plate consists of continental crust, the thinner, more dense oceanic plate tends to slide beneath the continental plate in a process called *subduction*. The force of the collision generates heat and pressure; water carried into the system reduces the melting point of the rocks; five to ten miles below the surface of the earth, they become a fluid magma (Fig. 8).

Figure 7. Plate boundaries on the eastern side of the Pacific Ocean. In some areas the plates are sliding past one another ("transform margin"). In others the plates are colliding head-on ("subducting margin"). The nature of the boundary controls the geological processes and history.
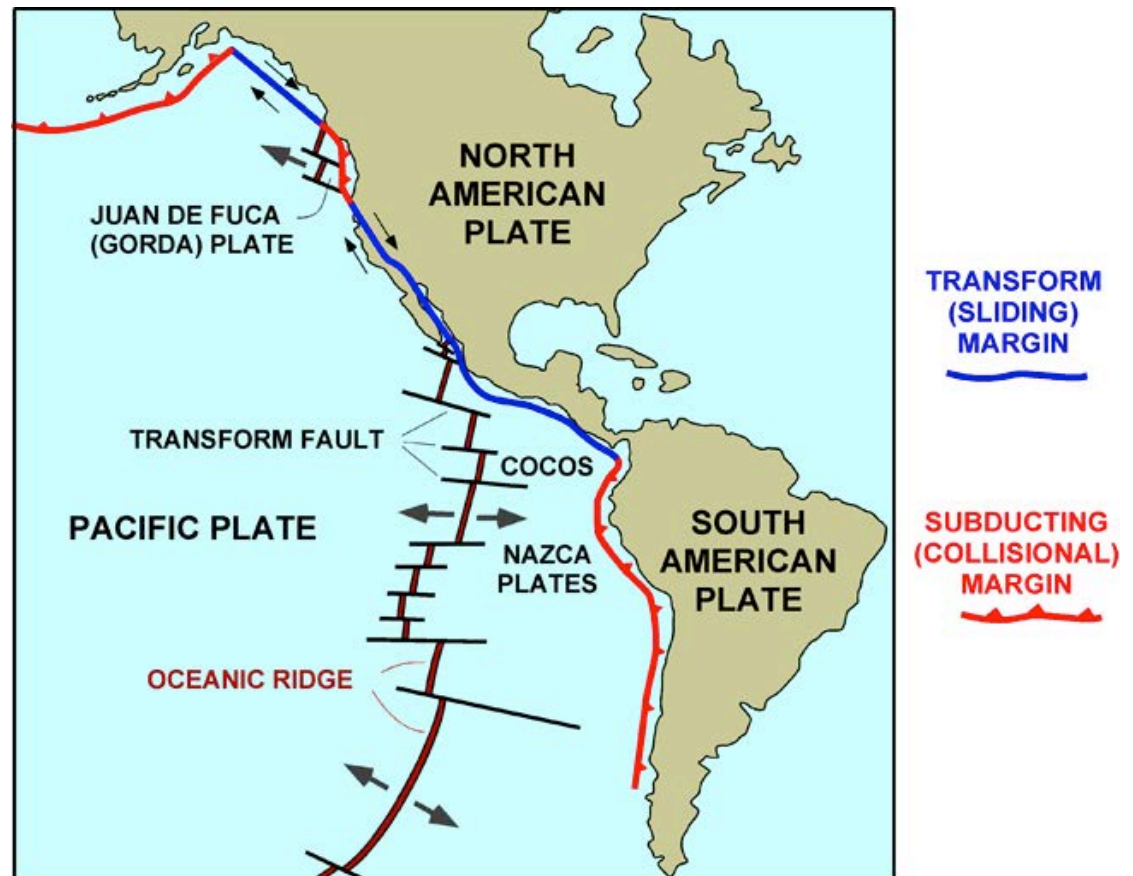
Figure 7 shows the distribution transform and subducting margins on the western sides of North and South American continents. Central and southern California lie on a transform margin on which the Pacific Plate is sliding to to the northwest relative to the North American Plate. Much of Northern California and the Pacific Northwest lie on a subducting margin. It is no accident that volcanoes in the "Ring of Fire" around the Pacific Ocean lies along the subducting margins" the Andes, Central America, the Pacific Northwest and the Aleutian Chain (Fig. 7). While damaging earthquakes can occur anywhere on an active margin, the areas of subduction are most likely to suffer giant, tsunami-generating earthquakes.

The geology of the Central California Coastal area long mystified geologists because it consists of a large elongate block of continental crust (the Salinia Terrain) (Fig. 9) encased in oceanic crust. In the 1980's a group of geologists thought that remnant magnetism in this rock indicated it originated from near the equator. Their subsequent analyses, however, did not support this hypothesis, and it was abandoned.

Most geologists today agree that Salinia is a southern extension of the Sierra Nevada that was rifted north by movement on the San Andreas Fault. The processes whereby this happened are shown in the following sections.
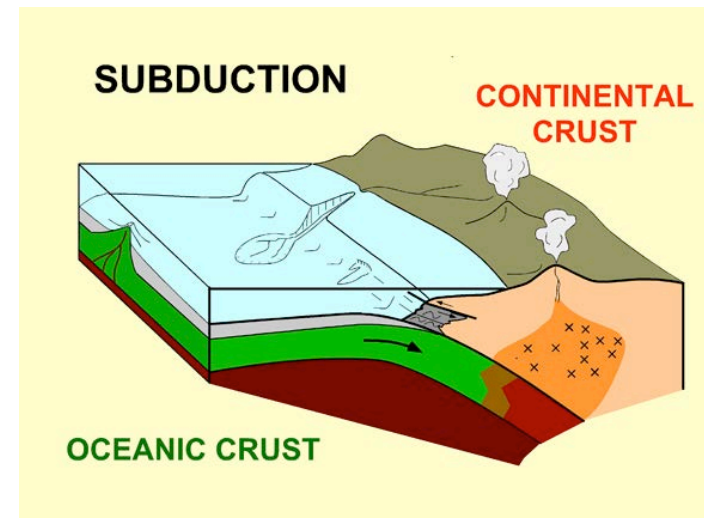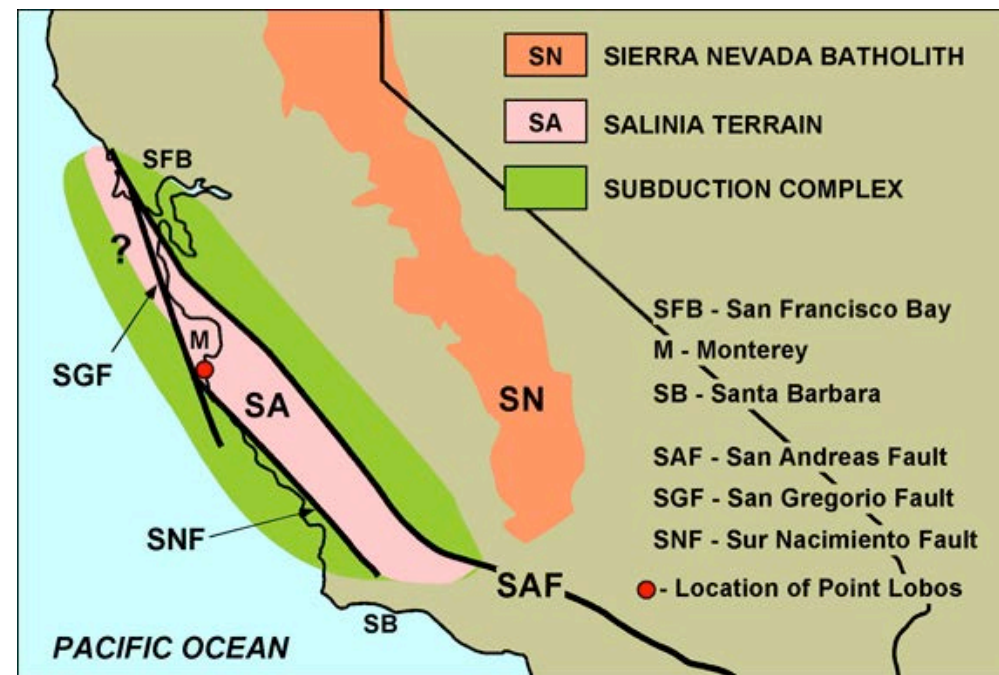

Figure 8. Subduction results where oceanic crustal plates collide head-on with continental crustal plates. The more dense oceanic crust is driven beneath the lighter continental crust. Water carried by this process into the depths of the earth lowers the melting point of the rocks. A magma of molten rock forms that can vent to the surface in the form of volcanoes

Figure 9. A large block of continental crust, called the "Salinia Terrane" (SA on this figure) long puzzled geologists because it lay sandwiched between masses of oceanic crust.
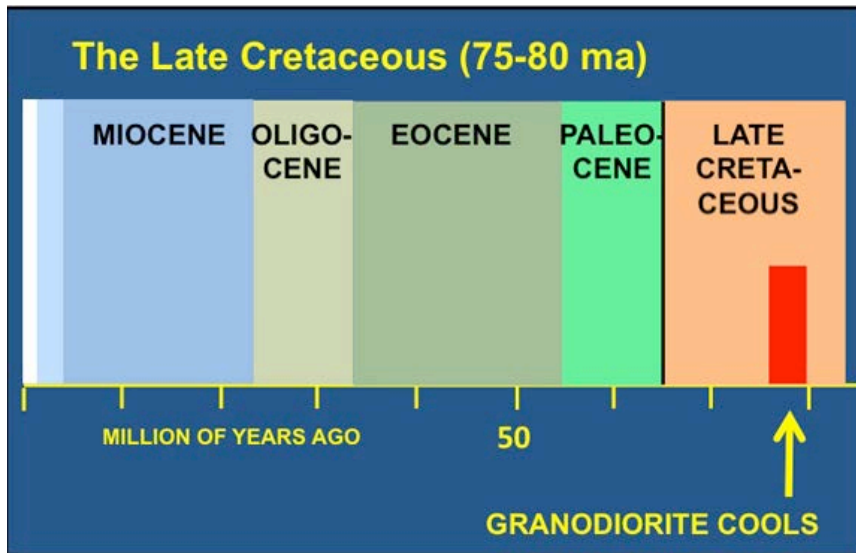
The Late Cretaceous (75-80 ma)

MIOCENE | OLIGO-CENE | EOCENE | PALEO-CENE | LATE CRETA-CEOUS

MILLION OF YEARS AGO   50

GRANODIORITE COOLS

80 MA

NORTH AMERICAN PLATE

PACIFIC OCEAN

SUBDUCTION ZONE (OCEANIC TRENCH)

FARALLON PLATE

cooling magma

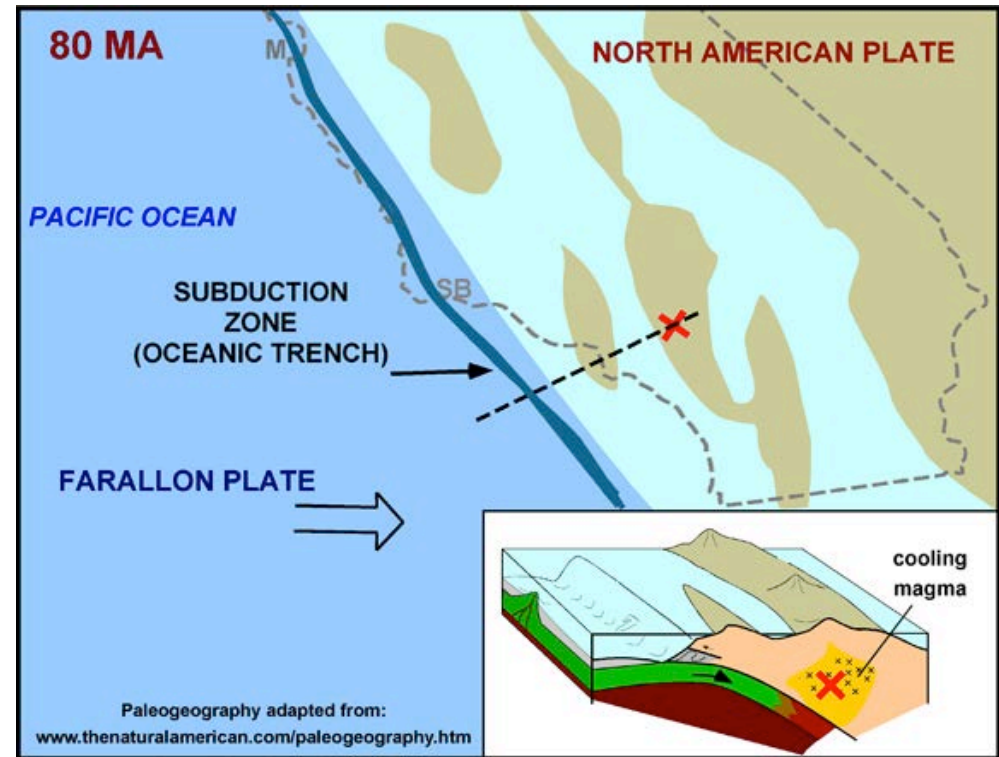Paleogeography adapted from: www.thenaturalamerican.com/paleogeography.htm

Figure 11. Eighty million years ago, a magma of molten rock material created by subduction was cooling somewhere in what today is Southern California. The newly crystallized solid rock will be called "granodiorite" because of its mineral composition. It is this rock that underlies Point Lobos and the entire Monterey Peninsula today. "M" and "SB" indicate the present-day locations of Monterey and Santa Barbara respectively.

The western margin of North America has long been the battleground between the continental plate and a series of large oceanic plates. For many tens of millions of years, a large oceanic plate, the Farallon plate, collided with the North American continent, generating a linear chain of large magma chambers (masses of molten rock). These masses cooled and were later uplifted to become the rocks that form the present-day Sierra Nevada Range. Eighty million years ago, the North American continent consisted of two landmasses separated by a large north-south seaway (Fig. 10). In the area of present-day Central and Southern California, magma chambers created by subduction of the Farallon plate were cooling, forming an igneous rock. In southern California, probably somewhat east of Los Angeles a granodiorite was crystallizing 5 miles or more below the surface of the earth (Fig. 11). This rock would later be exposed as the granodiorite at Point Lobos and the Monterey Peninsula.

How do we know when the granodiorite crystallized? The systematic decay of trace amounts of radioactive potassium in the feldspar provides a clock for dating the time of crystallization. Analyses indicate that this occurred during the Late Cretaceous period, nearly 80 million years ago (Kistler, R. W., and Champion, D. E., 2001, U. S. Geological Survey Open-File Report 01-453). Volcanoes may have erupted above the chamber, but their existence has since been lost to erosion.

The next geological event that is recorded at Point Lobos probably occurred in the late Paleocene Epoch, some 20-25 million years after the granodiorite crystallized (Fig. 12). By this time the granodiorite had shifted from its position miles below the earth's surface and now lay exposed on the continental margin (Figure 13). How this happened is still debated among geologists. Some think it was pushed westward and upward along a large thrust fault. In any event lying deep beneath the ocean's surface, it was covered by mud and rocky debris that slid down the ancient undersea slope. The resulting deposits are reflected by the shale and limestone breccias exposed at Gibson Beach. Rare, poorly preserved fossils in this rock indicate an upper Paleocene age.
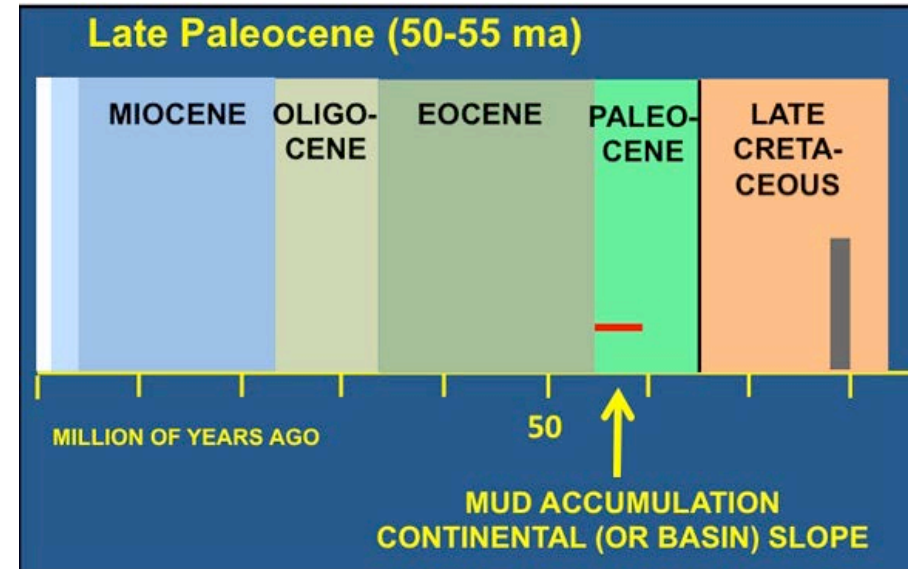

Figure 12. After the granodiorite crystallized nearly 80 million years ago, the next geological event recorded at Point Lobos appears to be in the late Paleocene Epoch, 55-60 million years ago. Dinosaurs no longer existed, having died out 65 million years ago at the end of the Cretaceous.
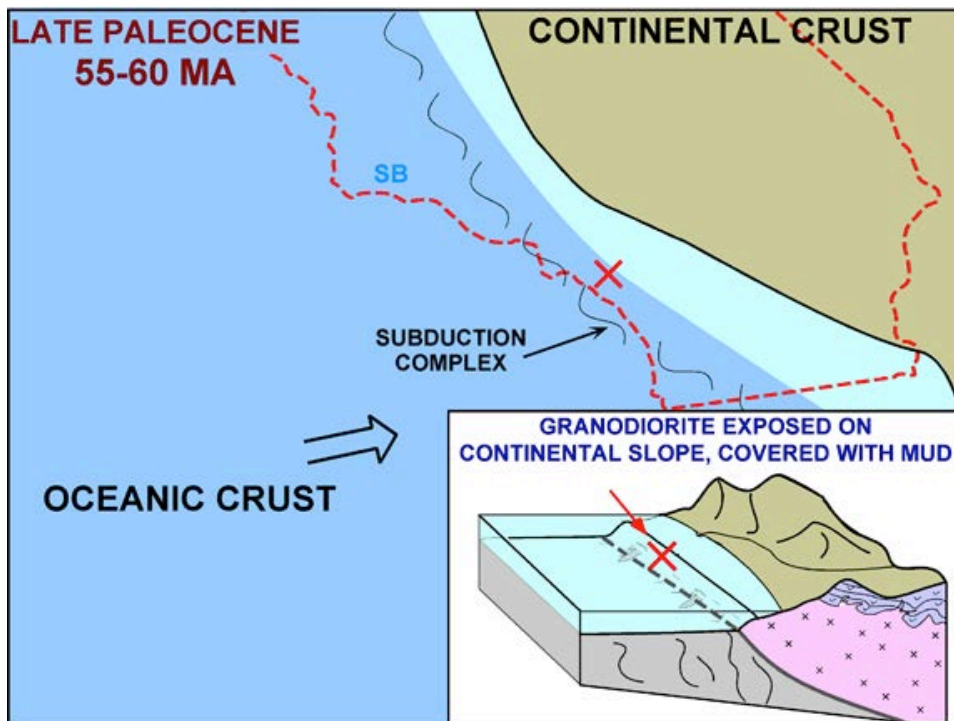

Figure 13. In the late Paleocene Epoch, 55-60 million years ago, mud accumulated on top of granodiorite exposed on the continental (or basin) slope. Consolidated long ago into rock, this material is exposed today in the cliff behind Gibson Beach. "SB" indicates present-day location of Santa Barbara.

The sedimentary rocks at Gibson Beach are considered part of the Carmelo Formation, a term given to deepwater sandstone, shale and conglomerate deposited in this area during the Eocene and Paleocene Epochs. They are quite different, however, from the rest of the Carmelo Formation at Point Lobos, which is composed primarily of conglomerate and sandstone. Fossils are very scarce in this latter rock, but microfossils collected from mudstone at Hidden Beach indicate deep (600 to 2000 feet) marine deposition during the early Eocene (Fig. 14). Sedimentary features in this rock support a deepwater origin. Since the sandstone and conglomerate seem to fill a valley cut into the granodiorite, the deposit is considered to represent the filling of a submarine canyon cut into an Eocene continental slope that existed in what is now southern California (Fig. 15).
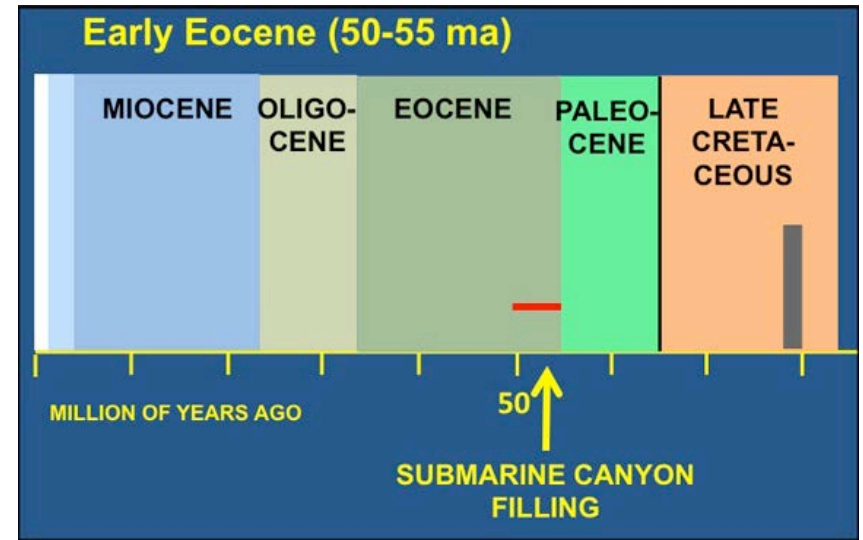

Figure 14. Most of the Carmelo Formation, the submarine canyon fill at Point Lobos, seems to have accumulated in the early Eocene, some 50-55 million years ago

Continued sedimentation buried the sand and gravel that accumulated within the submarine canyon. Under the weight of this overburden, the sand, gravel and mud gradually converted to rock: sandstone, conglomerate and mudstone, the material we see today at Point Lobos.
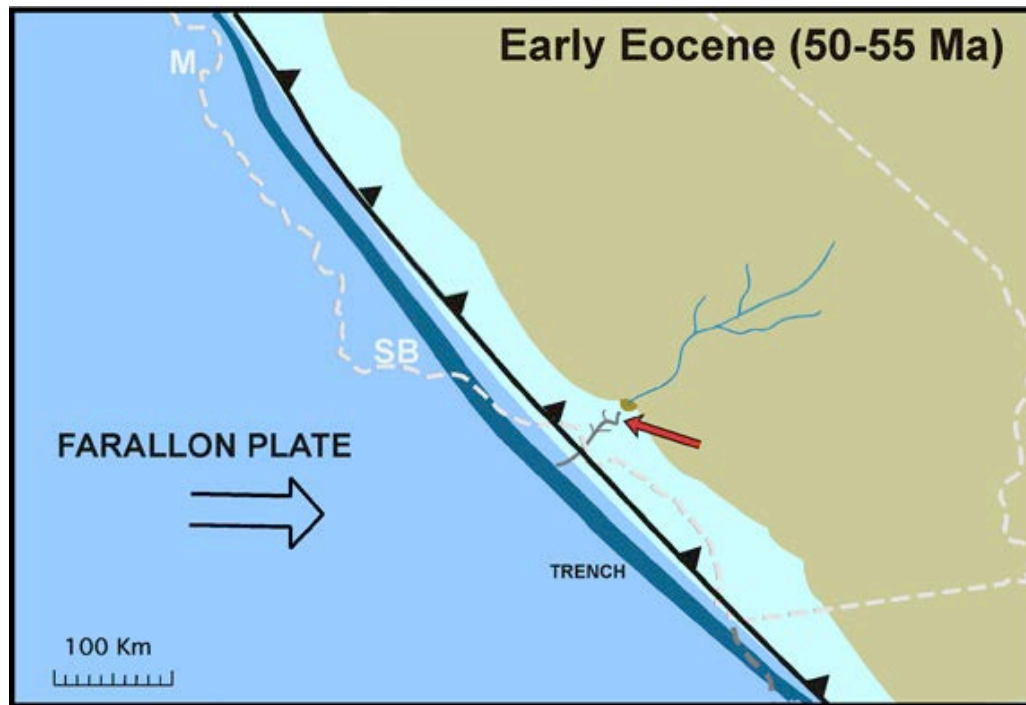

Figure 15. During the early Eocene, gravel, sand and mud accumulated in the submarine canyon that existed somewhere on an ancient continental margin in what today is Southern California.

Up to this point of time, our rocks of Point Lobos are still in Southern California, but that was about to change. Variations in the oceanic plate configuration in the middle Cenozoic were about to rearrange the western margin of North America. Around 40 ma, the process of subduction was consuming the Farallon Plate, and a giant plate to the west, the Pacific Plate, was approaching the continent (Fig. 16). Around 30 ma, the oceanic ridge that separated the Pacific and Farallon Plates grounded against the North American Plate and the Farallon Plate became divided into two smaller plates, The Juan de Fuca Plate to the north and the Cocos Plate to the south (Fig. 17).

The whole east Pacific oceanic plate system had a counter-clockwise rotation (a motion still seen in the northern part of the Pacific Plate today, see Figure 3). When the Pacific Plate encountered the North American Plate in the vicinity of the present mouth of the Gulf of California, the oceanic ridge may have dragged against the continental plate to the point that transform faults rotated into a parallel alignment with the plate boundary (Fig. 17). The transform fault separating the two plates was the ancestor of the present-day San Andreas Fault.
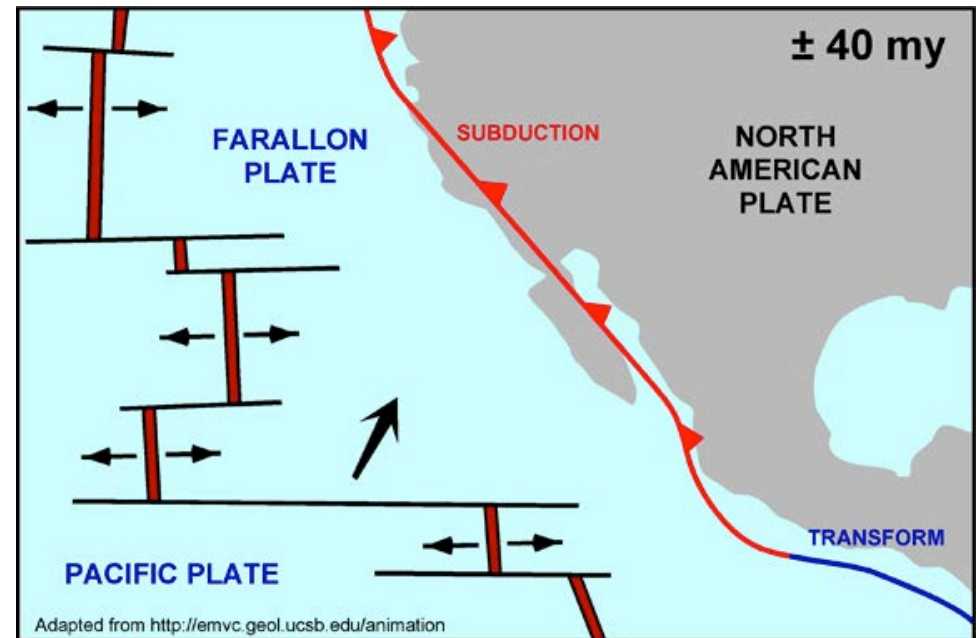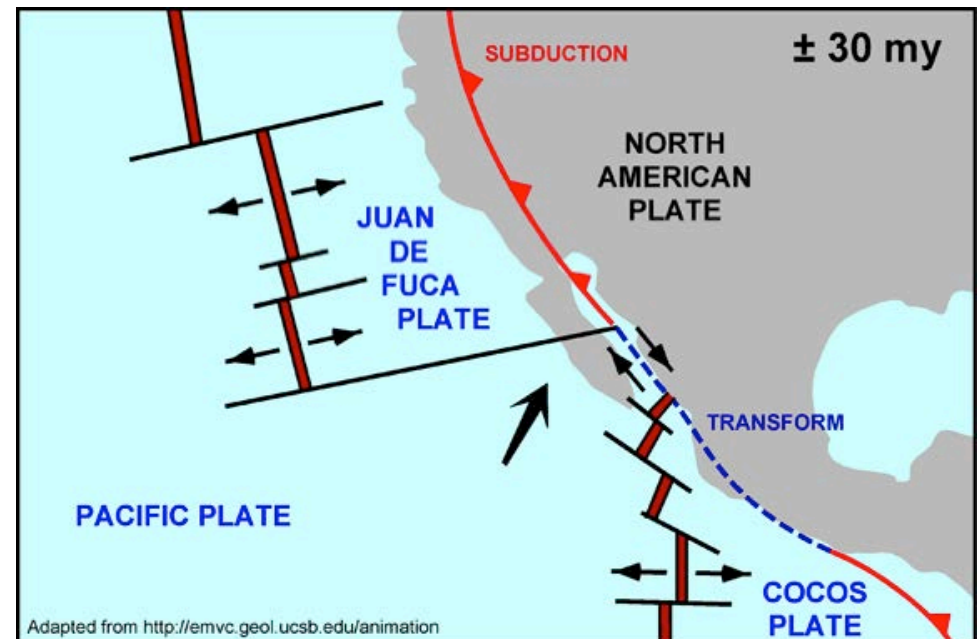

Figure 16. Around 40 million years ago, the Farallon Plate is being consumed by the process of subduction and the oceanic ridge separating the Farallon Plate from the Pacific Plate is beginning to encroach on the North American continent.

Figure 17. By 30 or so million years ago, the oceanic ridge separating the Farallon Plate from the Pacific Plate has encountered the North American continent. Because of its northerly movement relative to the North American Plate, the Pacific Plate drags against the continental plate, causing the oceanic ridge and the transform faults to rotate. The transform faults become parallel to the plate boundary where the two plates meet, and a transform margin begins to develop. The right-lateral displacement (the right side moves toward you) that characterizes the boundary between these plates today begins.

The next event that is recorded in this area occurs 27 million years ago during the Oligocene Epoch (Fig. 18). At that time, a volcano spewed lava (called "basaltic andesite") over what would become the Monterey Peninsula. The older Eocene sedimentary rock and the Cretaceous granodiorite had been uplifted and were exposed at the earth's surface. The basaltic andesite is not exposed at Point Lobos, but it does crop out at short distance away at either end of Carmel Beach (a couple of miles north of Point Lobos. It probably covered the Carmelo Formation and the granodiorite at what would later become Point Lobos, but has since been eroded away.

The volcanism may have occurred shortly before (or during) the passage of the "triple junction" where the boundary separating the Pacific and Juan de Fuca oceanic plates encountered the North American Plate (Fig. 19). To the north of this intersection of the plates, subduction occurs where the Juan de Fuca Plate encounters the North American Plate. To the south, the Pacific Plate slides by the North American Plate along a fracture, the ancestral San Andreas Fault.

Figure 18. Twenty-seven million years ago, volcanic rock accumulates atop the older Eocene and Cretaceous rocks.

Figure 19. Twenty-seven million years ago, volcanic rock accumulates atop the older Eocene and Cretaceous rocks which at this time lie at the earth's surface. In this cartoon, the "triple junction", where the Pacific, Juan de Fuca, and North American Plates meet, had not arrived yet at the location of the volcanism. It is quite conceivable, however, that it had arrived (so the volcanism occurred on the transform fault that we today call the Mendocino Fracture Zone) or had even passed to the north. (SF = present location of San Francisco, M = present location of Monterey, SB + present location of Santa Barbara)
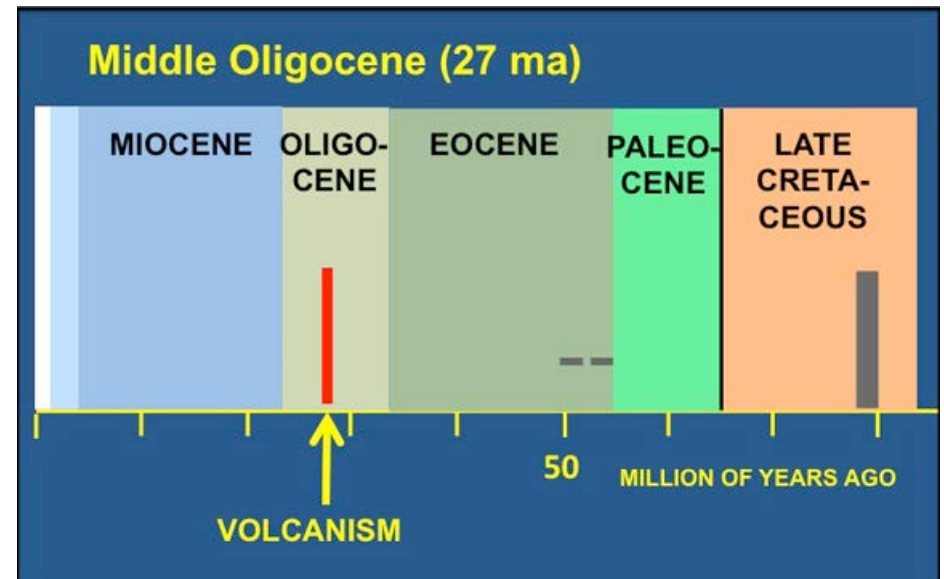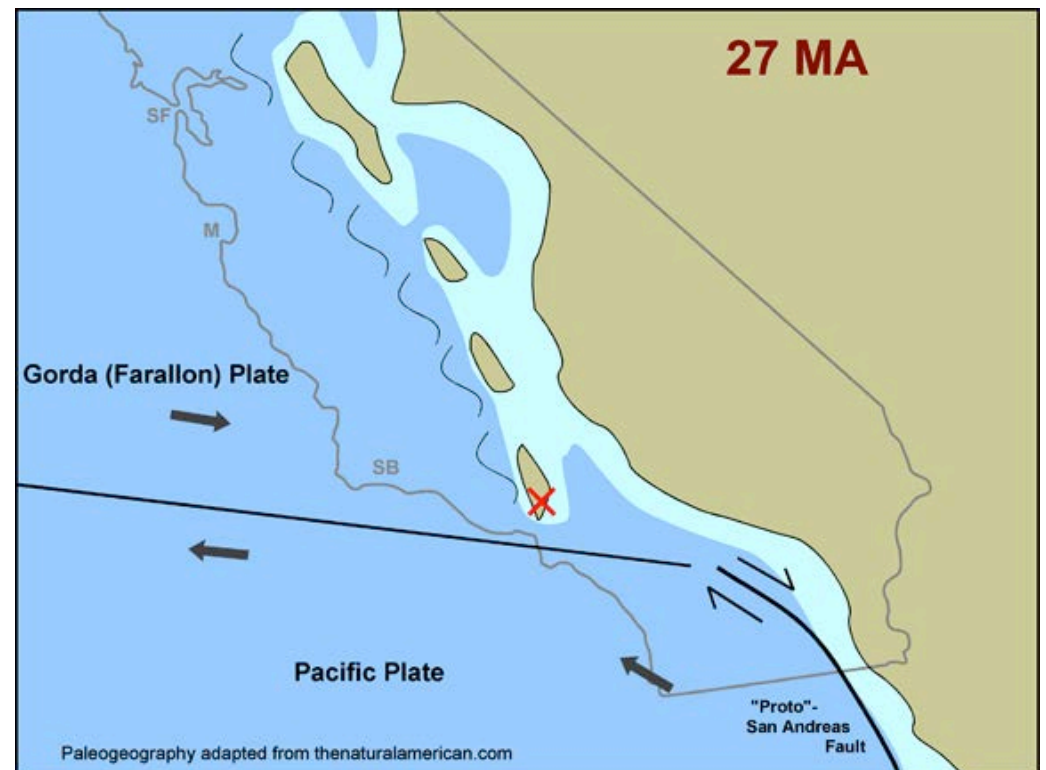
As the junction between the Pacific, Juan de Fuca and North American plates moved north, the rocks on the western side of the San Andreas Fault, now attached to the Pacific Plate, shifted north as well. During the transit to their present position, the landforms above the granodiorite and submarine canyon fill changed dramatically many times.

In what was probably early Miocene time (Fig. 20), the area was covered by a probable alluvial fan derived from a granitic upland in what today would be the southwestern part of Monterey Bay. A granitic boulder conglomerate (Fig. 21) crops out on the eastern side of Stillwater Cove, about 3 miles north of the Reserve. Near the contact with the Oligocene basaltic andesite, the conglomerate contains large angular fragments of the volcanic rock, demonstrating that the conglomerate postdates the volcanism. The size of the boulders implies a steep gradient to their source, and the stacking pattern of the boulders indicates that they were being carried to the south. The fan may have extended over the buried submarine canyon deposits and granodiorite of Point Lobos that are now exposed at Point Lobos.

Figure 20. Probably in the early Miocene Epoch, floods across an alluvial fan brought granitic boulders from the north to the area.

Figure 21. Granitic boulders in boulder conglomerate exposed along the east side of Stillwater Cove, about three miles north of the Reserve. Geological hammer for scale
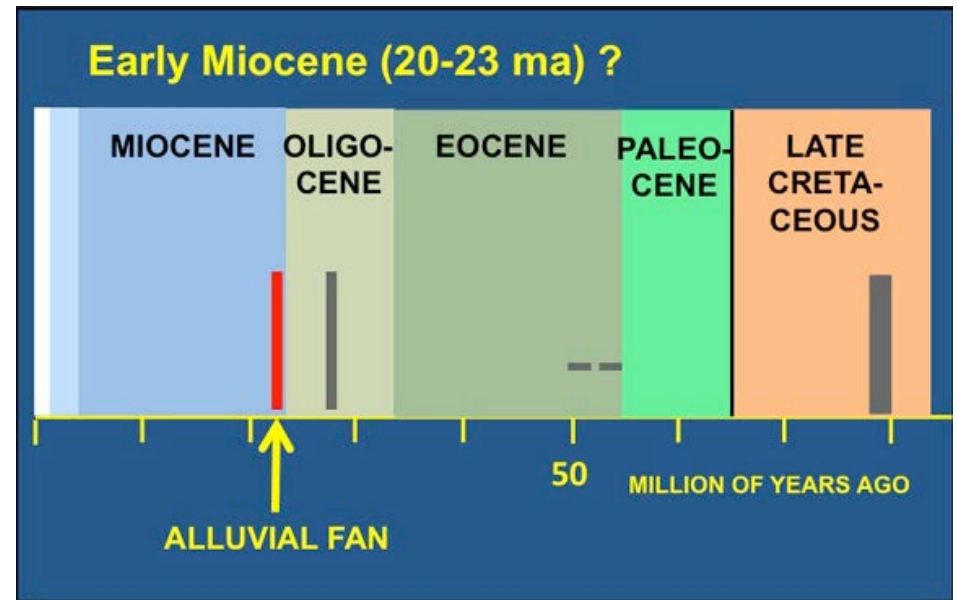
By middle Miocene time, 15-16 million years ago, (fig. 22), the landscape had evolved to a shallow coastal embayment with tidal channels and mudflats as the sea crept over the land. The resulting deposits are well exposed on Carmel beach after a winter storm. The land continued to sink as the middle Miocene progressed. By 11-13 million years ago, large marine basins indented the California shore (Fig. 21). The Eocene submarine canyon fill and the Cretaceous granodiorite lay beneath the floor of one of these basins. Extraordinary biological productivity generated huge sea floor accumulations of the remains of microscopic marine organisms, particularly diatoms. Buried and turned to rock, this material today composes the Monterey Formation, which forms white outcrops in the hills and road cuts in this area.
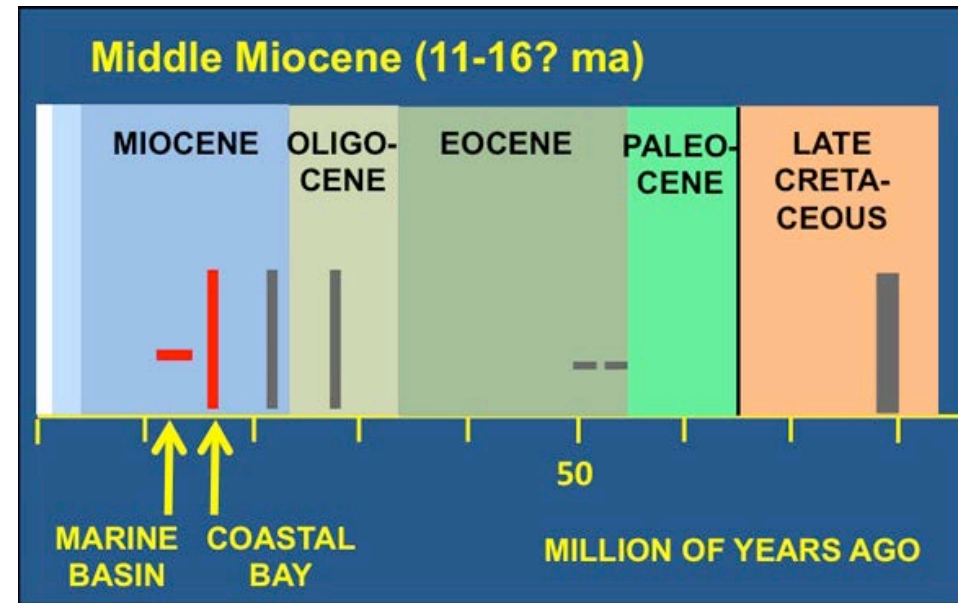

Figure 22. During the middle Miocene, the land that would become Point Lobos subsided into a deep marine basin.
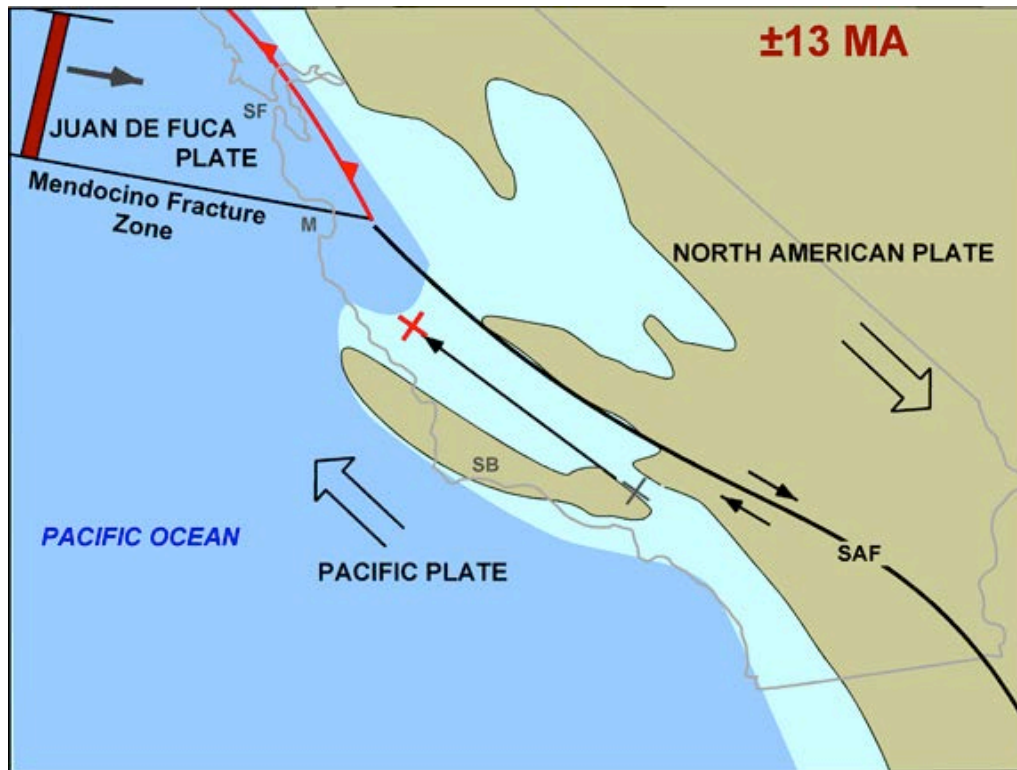

Figure 23. The California shoreline 11-13 ma was far different from that of today and may have looked something like that shown in the figure. A series of large separated marine basins existed. Our Point Lobos rocks (the red "X") had moved 150 miles or so northwest from their original position, relative to the part of California lying on the east side of the plate boundary (San Andreas Fault - SAF). They now lay beneath the sea floor in one of these marine basins in which great thickness of siliceous mud composed mostly of the tests of tiny marine organisms (diatoms).

In the late Miocene, 6 or so million years ago, the marine basins had mostly stopped subsiding and were filling with sediment (Figs. 24). Our Point Lobos rocks are 50-60 miles southeast of their present location, relative to the North American Continent. They will continue to move to their present location, and continue to move today, again relative to California east of the San Andreas Fault. The stresses imposed by the grinding of these two great plates against one another create "wrinkles" (think of putting your hands palm down on a table cloth and simultaneously moving one toward you and the other away from you).

The resulting "wrinkles" are manifested in the mountain ranges and basins that lie along the coast (Fig. 25), most of which have developed in the last few million years, and continue to actively grow today. Sedimentary deposits indicate that the area along the coast north of Santa Cruz and south of Monterey has been rising during the past several hundred thousand years, in contrast to the Monterey Bay Plain, which mostly has been subsiding. I estimate that the rocks at Point Lobos are currently being elevated at a rate of 6-7 inches per 1000 years.

If this rate of uplift remained fairly constant through time, the rocks here would have been some 500-600 feet lower a million years ago, and the coastline would likely have been occupied by the Monterey Formation. As uplift progressed, erosion removed the Monterey and the Carmelo Formation and the granodiorite emerged. It is probable that the physical shoreline feature that we know as Point Lobos came into existence several hundred thousand years ago.
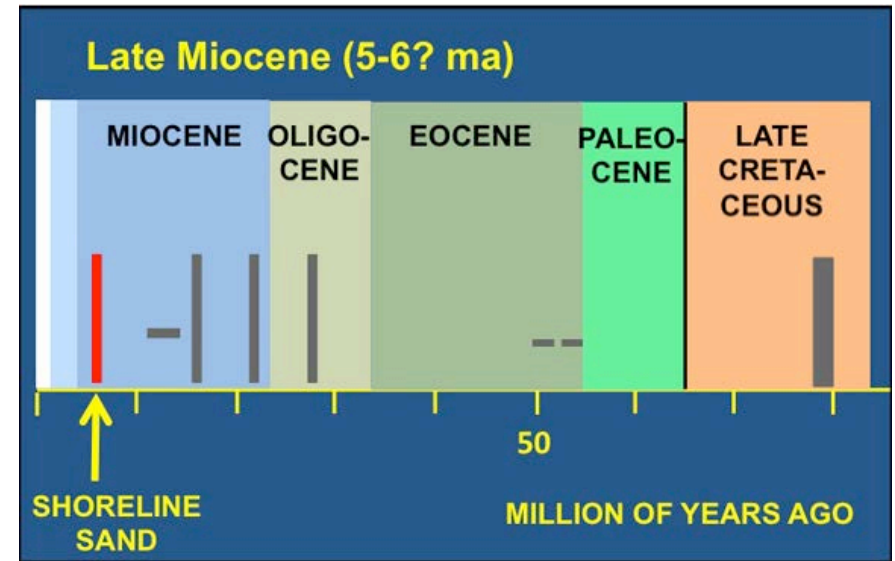

Figure 24. Toward the end of Miocene, the marine basins of the middle Miocene had mostly filled, and shallow marine sands were accumulating in this part of central California.

Figure 25. Forces associated with the grinding of the Pacific and North American Plates have created huge "wrinkles" that result in the coastal mountain ranges and lowlands. The upward and downward movements that respectively produced the ranges and lowlands are still active today.

The Pleistocene Epoch (Fig. 24) was a time of repeated glaciation. Massive ice sheets, 1-2 miles thick, several times covered then retreated from northern North America and Europe. The water that composed these great glaciers came from sustained snowfalls that were ultimately fed by the ocean. The transfer of this water out of the ocean caused a global fall of sea level. The transfer of water back to the oceans when the glaciers melted coincided with a rise in sea level.

As a result, Pleistocene sea levels fluctuated widely between lowstands during glacial episodes and highstands during interglacial times (Fig. 25). At the last lowstand (about 17,000 years ago), sea level lay about 130 m (more than 400 feet) below its present level. These fluctuations left their mark on the coast of Central California, especially in areas of uplift (Fig. 23).
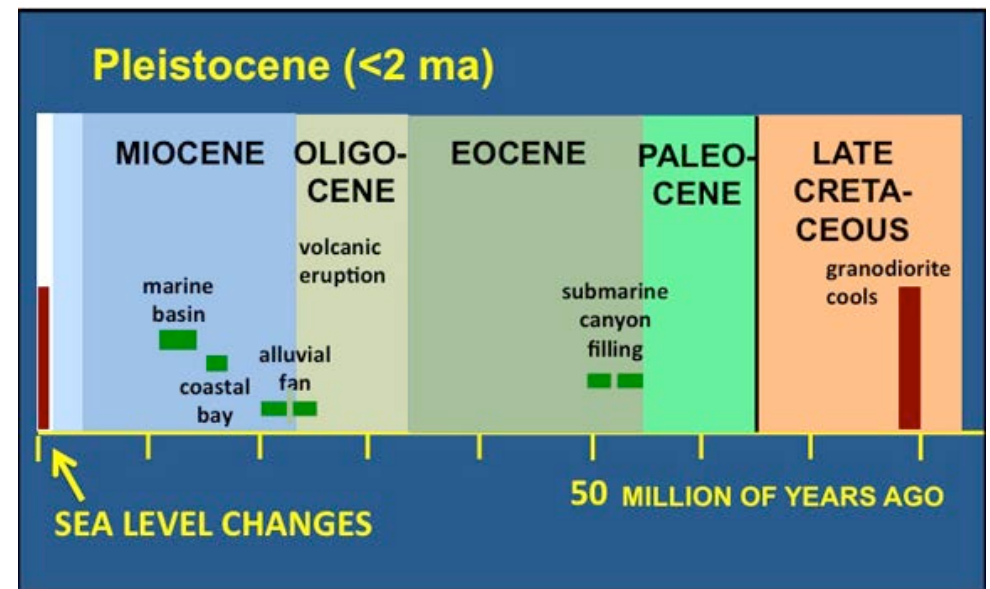

Figure 24. The Pleistocene Epoch extends from the present day back to about 1.8 million years ago. It was the time of glaciation (ice ages) on the earth
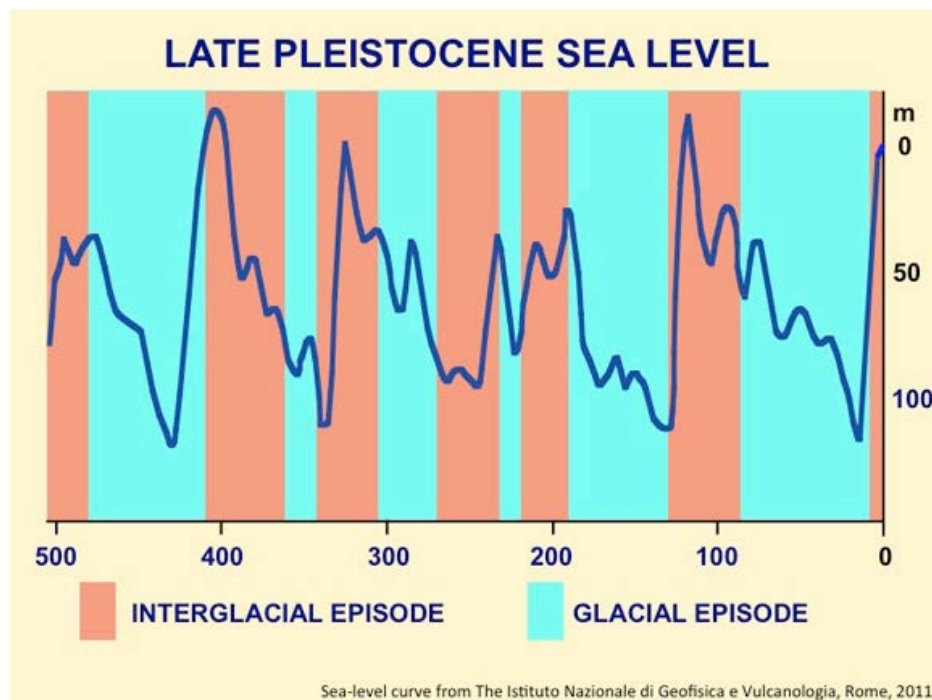

Figure 25. During the late Pleistocene Epoch, sea level rose and fell dramatically as the world alternated between glacial and interglacial episodes.

When sea level remains constant for a long period of time, the waves cut a very gently sloping platform that extends from the shoreline to a depth of about 30 feet (Fig. 26). The long periods of sea-level highstand shown in Figure 25 are sufficient to produce wave-cut platforms into the rocks along this coast.

While the late Pleistocene sea level was rising and falling in response to alternating glacial and interglacial conditions, the land at Point Lobos was slowly rising in response to stresses imposed by the plate motions. As it rose the old wave-cut platforms became elevated above the sea in the form of marine terraces. In an area of continuing uplift, the oldest terraces are the highest and generally the most poorly preserved. Figure 27 shows the uplifted marine terraces seen from the southeastern side of Moss Cove. The shoreline scar associated with the third terrace is visible as a faint horizontal trace on a distant hillside.
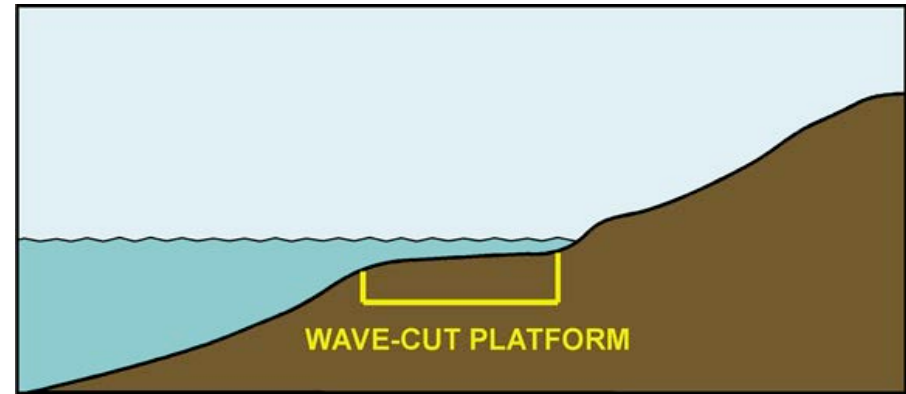

Figure 26. If sea level remains more or less constant for a long (thousands of years) period of time, the sea cuts a platform along the shoreline.

Figure 27. Elevated marine terraces on the northwest side of Point Lobos (Moss Cove in the foreground). Three terraces are visible. The lowest (and youngest) terrace is very well developed at the margin of Moss Cove. A second terrace is visible near the highway; Hudson House is built on it. A third terrace can be seen in the distance. The shoreline scar associated with this terrace is visible on the distant hillside.

When did Point Lobos materialize as a physical feature? The configuration of the Pleistocene terraces give us a clue. Figure 28 shows the likely shoreline associated with the lowest terrace. The headland is there and an older, larger version of Whalers Cove exists. This terrace formed at the last highstand of the sea about 100,000 years ago (Clark et al., 1997). The headland of Point Lobos did not exist during the development of the middle terrace (Fig. 29), although the higher parts of the Reserve might have projected as islands off a small headland developed at the present site of Rat Hill (Fig. 29).

The shoreline continues to change today. Large winter storm waves actively erode the coast along the south shore of the Reserve (Fig. 30). It seems likely that a few thousand years hence the coast there will be markedly different.
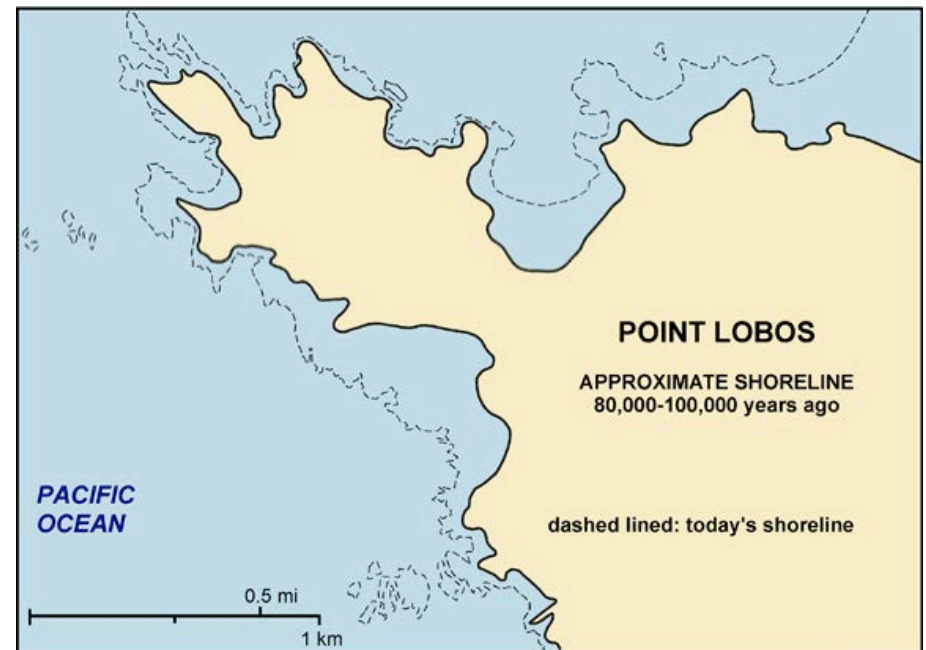

Figure 28. Inferred shoreline at the time of the lowest marine terrace development about 100,000 years ago.

Figure 30. Eroded shoreline at Weston Beach following a severe winter storm in 2008.
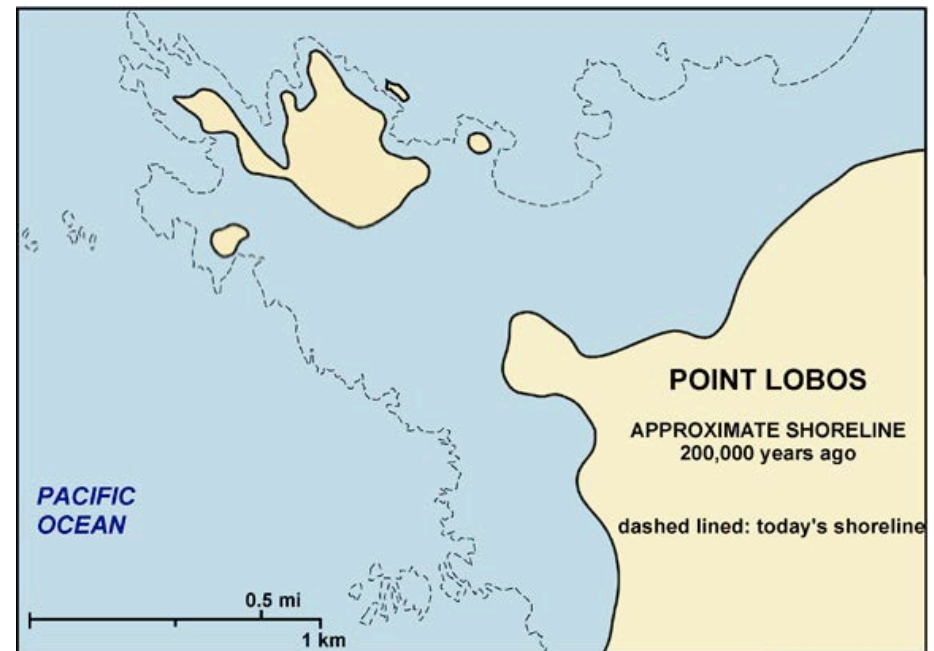

Figure 29. Inferred shoreline at the time of the middle marine terrace development between 120,000 and 200,000 years ago.

Figure 31 shows the broader geological aspects of the central California coast geology today. The Salinia terrane is interpreted as a southern extension of the Sierra Nevada batholith that was torn off the North American continent and driven north with the Pacific Plate. The movement continues today. Large active faults continue to reflect the movement along the boundary separating the Pacific and North American Plates (Fig. 32).

The great faults of Central California will continue to displace the rocks. In the geological future, Point Lobos will continue to travel to the northwest. Some geologists feel that rocks originally connected to those at Point Lobos have been carried as far north as Point Reyes. The vertical forces associated with stresses of the plate boundary will continue to warp the coastline. The power of storm waves will continue to assault the shoreline, inevitably and continuously remolding it. In the geologic future, Point Lobos, as we know it today will cease to exist. We are most fortunate to experience its present-day magnificence; like all things on earth, it will not last forever.
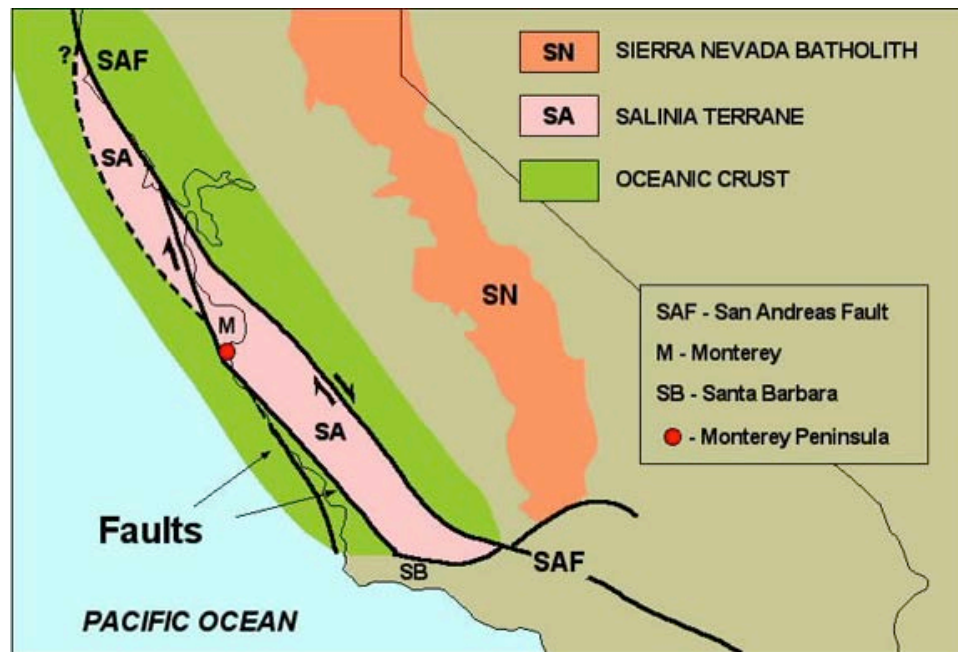

Figure 31. Major geologic elements of California's Central Coast. The Salinia terrane is considered by most geologists today to represent a southern extension of the Sierra Nevada Batholith, that because it lay on the seaward side of the San Andreas Fault was transported to the northwest as part of the Pacific Plate.

Figure 32. Major faults in the Monterey Bay area. Their displacements reflect the interaction of the great crustal plates that created them.