San Andreas Fault and Coastal Geology from Half Moon Bay to Fort Funston: Crustal Motion, Climate Change, and Human Activity

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Introduction

The geology of the San Francisco Peninsula reflects many processes operating at time scales ranging from hundreds of millions of years to a fraction of a human lifetime. We can attribute today's landscape in the San Francisco Bay area to three major processes, each operating at its own pace, but each interacting with the others and with subsidiary processes: (1) the slow, long-term motion of the North American tectonic plate as it moves relative to the northwest-moving Pacific Plate, and the smaller but important component of crustal compression between the two plates; (2) the more rapid changes in global climate during the last few million years, which have controlled the rise and fall of sea level and the succession of flora and fauna on land and along the coast; and (3) the very recent, explosive growth of human population and its related activity, as expressed in pervasive ecological impact and urbanization.

The oldest rocks in the region formed nearly 170 Ma (million years ago) under conditions very different from those in the San Francisco Bay area today, and rocks that were formed far apart have been juxtaposed during their later history. On a much shorter time scale, local climatic conditions and sea level have fluctuated dramatically since about 2 Ma during glacial and interglacial times. Very recent processes such as erosion and human activity have significantly affected the landscape on a still shorter time scale. The purpose of this trip is to examine the effects and interplay of these processes in producing some of the geologic features in this part of coastal California.

Mesozoic and Cenozoic Geologic Evolution of California

During the late Mesozoic and early Cenozoic, about 170 to 28 Ma, California lay along a convergent plate boundary. Modern convergent boundaries between a continent and an oceanic plate, such as the western edge of South America, typically include a volcanic arc on the continent, a forearc basin and accretionary complex seaward of the arc, a trench, and the unsubducted part of the oceanic plate farther seaward. The Mesozoic rocks of California reflect their origins in various parts of this setting (fig. 4.1). Granitic rocks of the Sierra Nevada formed below the arc of then-active volcanoes. The Coast Range Ophiolite represents the oceanic basement beneath part of the forearc basin, and sedimentary rocks of the eastern Coast Ranges (which we will not see on this trip) formed above this basement within the forearc basin. The oldest rocks in many parts of the Coast Ranges, called the Franciscan Complex, consist of deformed pieces of the accretionary complex (Page, 1981; Wahrhaftig, 1984).

About 28 Ma, the oceanic spreading ridge that lay west of the convergent boundary encountered the trench, and the North American Plate began to interact directly with the Pacific Plate (Atwater, 1970, 1989). Relative motion between these two plates is dominantly parallel to the plate margin, and the transform fault plate boundary of which the modern San Andreas Fault is a part began to develop and lengthen at that time (fig. 4.2). The northern end of this transform fault system, called the Mendocino triple junction, migrated northward and reached the latitude of Menlo Park about 10 Ma (Dickinson, 1981; Atwater, 1989). The geologic history of the San Francisco Bay area since about 10 Ma largely reflects the development of the San Andreas Fault system as the complex boundary between the North American and Pacific tectonic plates.

San Andreas Fault System

The San Andreas Fault is one of many faults comprising the transform plate boundary in the San Francisco Bay area (fig. 4.3). Most of these faults, such as the San Andreas, Hayward, Calaveras, and Greenville, are right-lateral strike-slip faults (the block on the west moves northward relative to the block on the east). Average slip rates are shown on figure 4.3. Other Bay-area faults are thrusts, in which one side of the fault moves upward and over the adjacent side. The unlabeled faults south of San José (fig. 4.3) probably are thrusts, and the San Gregorio Fault Zone may have components of both right-lateral strike slip and thrust slip.

The faults of the San Andreas Fault Zone juxtapose rocks with very different characteristics and histories. Throughout most of central California, the San Andreas Fault forms the boundary between areas underlain by Franciscan Complex rocks on the east side of the fault and areas underlain by granitic basement on the west (fig. 4.4). The areas underlain by granitic rocks constitute the Salinian block, which represents a piece of the old volcanic arc that has been transported northward along the San Andreas Fault and placed outboard (west) of the Franciscan Complex rocks.

One somewhat enigmatic fault on the San Francisco Peninsula is the Pilarcitos (fig. 4.3). In this area, Franciscan Complex rocks lie west of the San Andreas, and the Pilarcitos forms the boundary between blocks with Franciscan and Salinian basements. A traditional view is that the Pilarcitos represents a former trace of the San Andreas, and that the presently active trace on the Peninsula formed relatively recently (McLaughlin and others, 1996). The crustal block bounded by the Pilarcitos and the Peninsular strand of the San Andreas would thus be a piece of the former North American Plate that has been captured by the Pacific Plate and now moves to the northwest with the latter. The total amount of offset on the active trace of the San Andreas Fault since this capture is about 25 km. An alternative interpretation proposed by Wakabayashi (1999) is that the Pilarcitos is an old thrust fault not related to the San Andreas, which would require that most of the slip on the transform margin at this latitude has taken place on faults other than the San Andreas.

Many parts of the Bay area have experienced uplift and erosion or subsidence and sediment accumulation in response to compression normal to the San Andreas Fault system. Such vertical displacements would certainly accompany thrusting on the unlabeled faults in figure 4.3 and probably also accompany horizontal slip on the dominantly strike-slip faults. Sarna-Wojcicki and others (1986) estimated that the rate of shortening across the San Andreas Fault system is at least 10 percent of the rate of strike-slip motion over the past 6 m.y.

Sea Level Fluctuations During the Quaternary and Uplift of the Coast Ranges

Superimposed on slow lateral displacement and uplift of the faulted crustal blocks are the effects of the repeated rise and fall of the world oceans in response to changes in the amount of water stored in Earth's ice caps. High stands of the sea level are preserved as marine terraces, cut into the rising Coast Ranges. Multiple marine terraces can be observed on the coast near Santa Cruz and Half Moon Bay. The oldest terrace cut by sea level is now the highest; it has been uplifted the most because it has had time to be uplifted to a higher elevation. The youngest terrace above the modern surf-abrasion platform is the lowest; it has been uplifted only slightly, relative to the older terraces.

During the last major worldwide glacial maximum, about 20 ka (thousand years ago), sea level was as much as 130 m lower than it is now (fig. 4.5). The continental shelf was much more broadly exposed above sea level during this period, with the coastline as much as 35 km west of the present one. The Farallon Islands were then rugged hills rising above a broad, gently sloping plain, with the coastline lying to the west. At that time, there was no San Francisco Bay. The lowland that now forms the bay was a broad, forested valley. Local tributary rivers and streams converged near the center of the modern Bay area to join the huge, swollen river that rushed from eastern California past the present location of San Francisco and out onto the broad alluvial plain (now the continental shelf covered by the ocean). This huge river, bearing the runoff water from about 40 percent of California's land area during a cooler and wetter time than the present, must have been an imposing sight. Once the river met the broad, flat plain west of San Francisco, it meandered to the coast, just south of the Farallon Hills.

At that time, the valley that is now partly filled by San Francisco Bay contained stands of incense cedar, cypress, Douglas fir, and juniper, with an undergrowth of cocklebur and other brushy plants, and horned pond weed, elatine, and potamogeton in the wetlands. Meadows contained composites, chenopods, and grasses, as well as sage. Oak and sequoia, now so common in parts of the Bay area, were scarce or absent. Horse, bison, camel, and mammoth roamed the Bay valley, while smaller vertebrates lived in the brush and grass. Specimens of all of these fossils have been found in sediment exposed in deep pits excavated northwest of San José near Mountain View for San Francisco's garbage in the early 1970's. Fossil wood found in these deposits has yielded radiocarbon ages of 21 to 23 ka (Helley and others, 1972), close to the age of the last glacial maximum at about 18 ka. The pits are now filled and covered, and the area is the site of Shoreline Amphitheater, a large open-air theater where music concerts and other media events are staged. Even today, some spectators amuse themselves by lighting the methane that seeps out of the ground from the buried garbage below.

As the climate warmed after the last glacial period, glaciers began to melt, and the water stored in ice began to be returned to the oceans. Starting about 18 ka and continuing until about 5 ka, world sea level rose (fig. 4.6). The rise was not uniform, but punctuated by accelerations and slowdowns, and occasional stillstands, accompanied by formation of stable coastlines for perhaps hundreds of years. Sea level rose high enough by ~9 ka to extend into the valley of San Francisco Bay (Atwater and others, 1977). By ~5 ka, the sea level reached near its present position, and ceased to rise. Ages of dated Native American habitation sites around the bay, marked by shell middens (mounds of shells containing artifacts and often also used as burial mounds) date to about 5 ka, but no older. This suggests that older habitation sites are now below sea level, corresponding to earlier, lower stands of the ocean (Helley and others, 1972).

Effects of Human Activity on the San Francisco Landscape

Early Native American inhabitants of the San Francisco Bay area were probably a minor factor in affecting the form of the area's landscape. The human population was small, and the lifestyle of hunting and gathering was not particularly disruptive, but if humans contributed significantly to the late Pleistocene extinction of mammoths and other large animals in North America (Alroy, 2001), then they definitely had an impact on the ecosystem. With the transition from a gathering and hunting lifestyle of the early Native Americans to the agricultural economy and grazing practices of early Spanish and Mexican Californians, the original fauna and flora were gradually diminished, replaced, or eradicated. Rapid acceleration of change began with the influx of population that occurred after the discovery of gold in 1848. Timber harvesting, the expansion and intensification of agriculture accompanying the population influx, the growth of towns and cities, and industrialization all contributed to major changes in the flora, fauna, and landscape. Mining activities accelerated erosion in the hills and mountains, accelerating sediment deposition in the lowlands. Today, environmental issues including the decrease of wetlands in the Bay area (fig. 4.7) continue to be of concern.

The effects of human activity on the landscape in this area are likely to continue and accelerate into the future as population here continues to grow. The Bay area is likely to experience not only the effects derived from local population growth, but also from global effects induced by human activity. For example, continued global warming may result in a rising of sea level, with displacement of population from the lowest elevations (fig. 4.8).

Road Log

The trip begins at the U.S. Geological Survey in Menlo Park. The trip route and locations of the stops are shown on figure 4.9.

Mileage/Notes

0.0 Leave the U.S. Geological Survey parking lot and proceed north to Middlefield Road.

0.1 Turn left onto Middlefield Road.

0.4 Turn left onto Ravenswood Avenue.

1.1 Cross El Camino Real; street name changes to Menlo Avenue.

1.4 Turn left onto University Drive.

1.7 Turn right onto Middle Avenue.

2.5 Turn left onto Olive Street.

2.6 Turn right onto Oak Avenue.

3.2 Turn right onto Sand Hill Road.

4.9 Turn right onto Interstate 280 North.

7.4 Greenish-gray, rocky soil with little vegetation in the road cuts indicates the presence of serpentinite. Note the numerous small landslides in this weak material.

7.9 San Andreas Fault Zone occupies wide valley in left foreground.

11.1 Exit freeway at first Vista Point north of Edgewood Road.

11.5 Park at Vista Point. Proceed up path to the west to view Crystal Springs Reservoir.

Stop 1—San Andreas Fault Overlook—Crystal Springs Reservoir

This reservoir occupies a portion of the San Andreas Fault Zone. About 4 m of right-lateral strike slip was recorded (by offset fences, dams, and other features) in this area during the 1906 San Francisco earthquake. Maximum displacement on the fault was ~6 m farther to the north, and the entire rupture length was 430 km. The magnitude of the earthquake was determined to be ~ 8.3 on the Richter scale, though later moment-magnitude calculations yield a lower value of ~7.8 (Thatcher, 1990). The earthquake was felt from southern Oregon to southern California and as far east as central Nevada (Ellsworth, 1990). Although the dams at Crystal Springs Reservoir and at San Andreas Lake farther north held during this earthquake, the water pipes supplying the city were ruptured in many places, so that water could not be delivered to stop fires that had broken out after the earthquake. It was the fire much more than the ground shaking that contributed to the great damage of the 1906 earthquake (Ellsworth, 1990).

Rocks of the Jurassic-Cretaceous Franciscan Complex occupy the northeast side of the fault, whereas Cretaceous granitic rocks of the Salinian block lie to the southwest. This contrast is part of the basis for interpretations of up to 320 km of cumulative right-lateral displacement along the San Andreas Fault. Clahan and others (1995) estimated an average slip rate of 17±3 mm/yr in this area since 2 ka (fig. 4.3).

Although none of the rocks here are true "in place" outcrops, fragments on the ground and in the rock wall come from bedrock nearby. Blocks of serpentinized ultramafic rock along the path represent metamorphosed oceanic mantle, probably from the Coast Range Ophiolite. Large boulders near the path include Franciscan Complex greenstone (metamorphosed basalt) and radiolarian chert from the accreted oceanic plate.

Exit Vista Point and return to Interstate 280.

11.8 Reenter Interstate 280.

14.7 Exit Interstate 280; take Highway 92 West to Half Moon Bay.

15.9 Cross Crystal Springs Reservoir within San Andreas Fault Zone.

17.9 Cross summit on Highway 92. Valley in foreground is occupied by Pilarcitos Creek, and the Pilarcitos Fault runs parallel to the creek near the bottom of the valley.

18.6 Several terraform-sculpted retaining walls were recently installed in this area in order to help stabilize the slopes with a minimum of right-of-way expansion.

23.1 Turn right onto Highway 1 North.

26.3 Turn left into parking lot at Pillar Point Harbor.

Stop 2—El Granada Beach

This flat coastal area is a marine terrace that formed during a relatively higher stand of the sea about 100 ka. Note the old wave-cut cliffs to the east and partly dissected higher terraces. Although originally incised horizontally into the rising terrane, the ancient terrace surface is gently folded into a northwest-plunging syncline (fig. 4.10). The lowest elevation coincides with the deepest part of the embayment at Half Moon Bay; the terrace surface rises both to the north and to the south (Lajoie, 1986).

The higher elevation of this same terrace west of the Half Moon Bay airport has been caused by uplift on the Seal Cove Fault, one splay of the San Gregorio Fault Zone. The amount of uplift on the Seal Cove Fault is thought to be small compared to its strike-slip displacement, but the rates of modern and recent strike slip on this fault are controversial (Simpson and others, 1997; Sedlock, 1999).

The deformed marine terrace consists of eroded rocks of the Miocene to Pliocene Purisima Formation (about 5 to 3 Ma) overlain by a thin veneer of younger, unconsolidated sediment. The Purisima Formation forms the relatively resistant rocks that make up Pillar Point to the west of the Seal Cove Fault. At El Granada, however, the unconsolidated sediment at the top of the terrace is at sea level, and erosion by waves is much more rapid here. The rate of coastal erosion became even greater after installation of the breakwater in 1960 (Mathieson and others, 1997).

Exit parking lot and return to Highway 1.

26.4 Turn left onto Highway 1 North.

27.9 Half Moon Bay airport on left. This area provides another view of the terrace, old wave-cut cliffs, and Seal Cove Fault described at Stop 2.

30.9 Crossing the marine terrace at Montara Beach.

31.4 First steep outcrops of granitic rocks.

32.1 Turn right into parking area.

Stop 3—Salinian Granitic Rocks

Rocks in this area are Cretaceous (about 90 Ma) granitic rocks of the Salinian block. These quartz-rich plutonic rocks, very similar to granitic rocks of the Sierra Nevada, formed several kilometers below the land surface within what was then an arc of active volcanoes in southern California. The rocks have since been transported northward along the San Andreas Fault and uplifted, and the overlying volcanic, sedimentary, and metamorphic rocks have been eroded. Because these granitic rocks are much more resistant to erosion than the sedimentary materials at Stop 2, the coast is much steeper here.

Leave parking area and return to Highway 1.

32.2 Turn right onto Highway 1 North.

33.1 Highway 1 crosses a large landslide complex here near Devil's Slide. The landslide is mostly or entirely within sedimentary rocks that overlie the Salinian granitic rocks, and it has been active for many years. The most recent repairs were made after a slide in 1995 caused the road to be closed. The road was reopened after 5 months; although it has remained open since then, Caltrans personnel maintain that the repairs must be thought of as temporary (Williams, this volume).

33.6 Rocks on the right are Paleocene turbidites (younger than about 65 Ma).

34.3 Pilarcitos Fault runs through the valley ahead.

36.2 Turn left onto Rockaway Beach Avenue and take immediate right onto Old County Road.

36.4 Turn left at end onto San Marlo Way.

36.5 Park in lot.

Stop 4—Pacifica Quarry

At Pacifica Quarry near Rockaway Beach, Franciscan Complex rock types include limestone, greenstone dikes, and mélange that are part of the Permanente terrane. This discussion is slightly updated from Larue and others (1989).

The greater than 70 m-thick section of Calera Limestone Member of the Franciscan Complex (previously quarried for cement) includes dark gray to black strata overlain by beige to light gray strata; interbedded chert probably formed due to diagenesis (very weak metamorphism). The limestone consists chiefly of planktonic forams and micritic (muddy) groundmass, with minor coccoliths, and yields early Albian to mid-Cenomanian ages (about 105 to 94 Ma). Black limestones probably accumulated under anoxic conditions. Similar, probably correlative, rocks currently are quarried at Permanente (west of San José).

Greenstone, or metamorphosed basalt, is present only in dikes that cut the limestone on the west wall of the quarry, but similar rocks crop out in large, massive bodies a few kilometers north. Geochemical analysis of immobile elements and relict clinopyroxenes were used to infer that the basalts were emplaced either at a spreading center (MORB) or at an oceanic plateau or island (within-plate tholeiite)—the elemental composition of these basalts more closely match the composition of rocks in these oceanic settings than basalts found in continental interior regions. Some greenstone dikes contain lawsonite and jadeitic clinopyroxene, which indicate that the dikes (and their limestone host) experienced blueschist-facies metamorphism (low temperatures, high pressures).

Mélange, defined as a mixture of blocks in a weaker matrix, here consists chiefly of limestone blocks in shale. Elsewhere in the Permanente terrane, mélange blocks include greenstone, sandstone, and blueschist; matrix is either shale or serpentinite.

A likely geologic history is as follows (fig. 4.11): (1) the limestone accumulated (not as a reef complex) atop basaltic oceanic crust (not exposed here) on a seamount, (2) few basaltic dikes intruded the limestone sequence, perhaps near a transform fault that leaked basaltic magma, (3) the fossil seamount was subducted beneath western North America to depths sufficient for blueschist-facies metamorphism (at least 15 km), and (4) complex faulting juxtaposed the limestone, basalt, and mélange during subduction, exhumation, or both.

Some workers have interpreted paleomagnetic data to indicate that the limestone was deposited at a latitude of 22°N and shifted northward on the Farallon Plate or (after accretion to North America) within the Franciscan Complex (Tarduno and others, 1985). However, others have argued that the Calera Limestone Member, like much of the Franciscan, was remagnetized after its initial magnetization, invalidating the paleomagnetic argument for long-distance transport. The presence of tropical microfauna in the limestone, however, tends to support the initial hypothesis of long-distance northward transport (Sliter, 1984).

Leave parking lot and proceed toward Highway 1.

36.6 Turn right onto Dondee Way.

36.7 Turn left onto Rockaway Beach Avenue.

38.7 Turn left onto Highway 1 North.

39.5 Take Manor Drive exit. Keep left on Oceana Boulevard.

39.9 Turn left onto Manor Drive. Cross Highway 1 and take immediate right onto Palmetto Avenue.

40.8 Turn left onto Westline Drive. Keep left along the coast to parking lot.

41.2 Park and walk northward to view area.

Stop 5—Mussel Rock

The San Andreas Fault crosses the shoreline near here and passes offshore of San Francisco to the north. The steep cliffs on the northeast side of the fault are composed of weakly consolidated sediment of the Merced Formation and related units, which are Pliocene and Pleistocene in age (perhaps about 3 Ma to less than 50 ka).

The Merced Formation and related units are more than 1700 m thick and are composed of sediment deposited in a variety of coastal settings, ranging from shelf through nearshore to nonmarine environments (Clifton and Hunter, 1999). Environments can be determined from the nature of the bedding and other lithologic criteria, and comparison of these features with those found in modern settings. Independent confirmation of depths can also be obtained from fossils present in the sediments by comparing these to the same or similar organisms living today in the corresponding environments and water depths. The sediment exposed in the cliffs contains mostly shelf deposits in the lower part of the Merced Formation near here, and the proportion of shallow-water and nonmarine facies increases farther north in younger layers. However, there is a cyclic, smaller-scale repetition of alternating deeper and shallower environments that is superimposed on the generally shallowing trend (Clifton and Hunter, 1999). These smaller-scale cycles represent packages of sediment deposited during sea-level oscillations caused by climate change during deposition.

The repeated occurrence of shallow-water deposits in this thick sequence indicates that the sediment accumulated in an area that was slowly subsiding over millions of years, and accumulation kept approximate pace with subsidence. The fact that these young strata are now tilted and exposed well above sea level shows that this same area has recently changed to a site of uplift.

There are many examples of slope failure in the weakly consolidated Merced Formation along the cliff face. A narrow bench that crosses the cliff face was originally part of the Ocean Shore Railroad, constructed in 1905 and 1906, then abandoned in 1920. Some time after 1933, the right-of-way was widened to accommodate California Highway 1, the Ocean Shore Highway, which was maintained here with great difficulty, expense, and frequent shutdowns. The road was heavily damaged by landsliding in the March 22, 1957 earthquake (fig. 4.12) and was abandoned in 1958 (Sullivan, 1975).

The area became heavily developed between 1950 and 1960. Much of the rolling topography atop the bluffs was leveled, and subdivisions were put in, extending close to the cliff edges. Many homes close to the cliff were damaged, condemned, and destroyed as a result of landsliding. Landsliding and damage to the houses continues to the present.

Return to parking area and exit toward Westline Drive.

41.5 Turn left onto Skyline Drive (sign is missing; turn at change in pavement) and immediately left again onto Westline Drive.

41.7 Westline Drive closed ahead due to landsliding. Turn right onto Rockford Avenue.

41.9 Turn left onto Longview Drive.

42.0 Former continuation of Westline Drive on left. Homes near the bottom of this hill have been removed recently.

42.1 Turn left onto Skyline Drive.

42.3 Houses that formerly lined this street on the seaward side have been removed because of landslide damage.

42.9 Turn left onto Northridge Drive.

43.2 Northridge Park with view of Wood’s Gulch to north.

43.3 Turn left onto Avalon Drive.

43.4 View of Wood’s Gulch on left. Recent work on the south side of Wood’s Gulch involved extensive terracing and installation of drains.

43.5 Turn right onto Westmoor Avenue.

43.6 Turn left onto Skyline Boulevard.

44.8 Former entrance to Thornton Beach State Park, now closed because of landsliding. More landslide damage is evident ahead.

46.3 At John Muir Drive, make a U-turn and return southward on Skyline Boulevard.

46.6 Turn right into Fort Funston. Keep right and proceed toward hang glider launch area.

47.0 Park in parking lot. Walk toward the ocean, keep to the left of the hang-glider launch area, and hike down the path to the beach. NOTE: this is a fairly strenuous hike. Turn right and hike northward along the beach to outcrops.

Stop 6—Fort Funston

The Merced Formation here is Pleistocene in age (about 0.5 Ma) and includes excellent examples of several different sedimentary environments. Clifton and Hunter (1999) identified 41 distinct stratigraphic divisions within the Merced

Formation and related units; we will be examining exposures in their units R, S, and T. Excellent descriptions of the stratigraphy and the sedimentary features here are presented by Hunter and others (1984) and Clifton and Hunter (1987, 1999).

Marine facies in this part of the section are quite diverse. Subtidal deposits include dark, fossiliferous and bioturbated sand in unit R, parallel laminated and burrowed sand and silt in unit S, and cross-bedded gravel and pebbly sand in unit T. The differences between these shallow-marine facies probably reflect different influences of tidal currents, waves, and biological activity during accumulation of the different units. Intertidal and lower supratidal deposits in each of these units include parallel laminated sand with local concentrations of heavy minerals. The nonmarine deposits in each unit consist mostly of wind-blown sand, locally modified by soil-forming processes. Notable additional elements in the nonmarine facies are pebbly fluvial sediment at the top of unit R, the Rockland ash bed [probably 400 ka (Sarna-Wojcicki and others, 1985) but possibly about 610 ka (Lanphere and others, 1999)] in unit S, and well developed, water-worked backshore deposits, especially in unit T. The part of the Merced Formation exposed here contains a larger proportion of shallow-water and nonmarine deposits than the older part of the formation at Stop 5.

Each of the units in this part of the Merced Formation consists of a shallowing-upward sequence, with shallow-marine deposits at the base that are overlain by intertidal facies and then capped by sediment deposited above sea level. At the top of each unit is an unconformity, which represents a time when sediment was eroded or not deposited. At each unconformity, nonmarine deposits of the lower stratigraphic unit are overlain by marine deposits of the next higher unit.

As at Stop 5, the repetition of marine units shows that this area was subsiding during the deposition of the Merced Formation. At the same time, Pleistocene ice sheets were expanding and melting repeatedly, changing the volume of water in the oceans and causing worldwide fluctuations in sea level exceeding 100 m. We correlate the major unconformities in this part of the section to times of low sea level, and we attribute the marine deposits above the unconformities to flooding as sea level rose. In each of the units, the shallowing-upward sequence formed mainly by progradation of the coast during the sea-level high stand and, perhaps, during the early stages of the next sea-level fall. The punctuated nature of the stratigraphic sequence here is thus the result of repeated worldwide changes in sea level superimposed on long-term local subsidence.

Studies of the mineralogy of sediment in the Merced Formation indicate that the lower two-thirds of the formation contains sediment derived from local sources within the central Coast Ranges. Minerals in the sediment are similar to those found in streams draining various parts of the Coast Ranges within the vicinity of San Francisco Bay. Heavy minerals can be more useful and diagnostic of sediment provenance than fine rock fragments and light minerals. Among the heavy minerals present in the lower units are glaucophane, jadeite, actinolite, omphacite, and pumpelleyite. These are minerals typical of Franciscan Complex metamorphic rocks found in the Coast Ranges. About two-thirds of the way up in the Merced Formation section, however, there is a sudden and dramatic change in mineralogy. A flood of fine volcanic rock fragments and minerals appear that are evidently derived from the Sierra Nevada and the southern Cascade Range, with only a minor percentage of Coast Range-derived sediment. Heavy minerals such as hornblende, hypersthene, and augite predominate. These data indicate that sediment derived from the interior of California was suddenly introduced into the Merced embayment at the time of the change in the mineral assemblage (Hall, 1965). This geological event marks the inception of river drainage from the Great Valley of California through the area of the modern San Francisco Bay. Prior to this event, Great Valley drainage had been channeled through an outlet at the south end of the Great Valley. The change in mineralogy occurs about 115 m below the Rockland ash bed. Thus, by interpolation, this major change in the Great Valley drainage is inferred to have occurred sometime about 650 ka (Sarna-Wojcicki and others, 1985).

Return to parking lot. Exit parking lot and return to Skyline Boulevard.

47.2 Turn right onto Skyline Boulevard.

48.3 Turn left onto John Daly Boulevard.

49.5 Turn right onto Interstate 280 South.

63.9 Crystal Springs Reservoir on right with dam out of view below freeway. The canyon on the left leads to the city of San Mateo.

75.4 Exit Interstate 280 at Sand Hill Road and proceed east toward Menlo Park.

79.6 Turn left onto El Camino Real.

80.4 Turn right onto Ravenswood Avenue.

81.0 Turn right onto Middlefield Road.

81.3 Turn right onto Survey Lane.

81.4 Enter U.S. Geological Survey parking lot. This concludes the road log for this trip.

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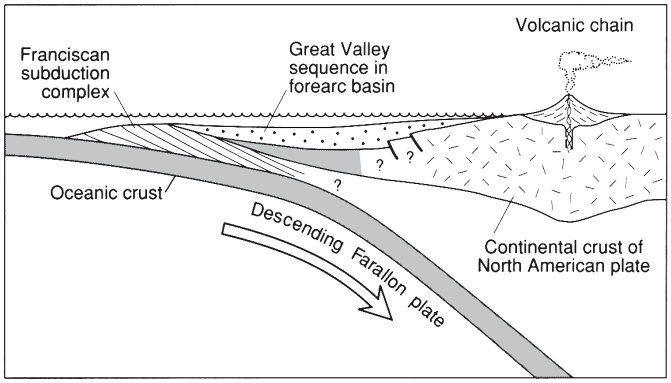

Figure 4.1. Schematic cross section showing California as an Andean-type continental margin during late Mesozoic time (from Irwin, 1990).

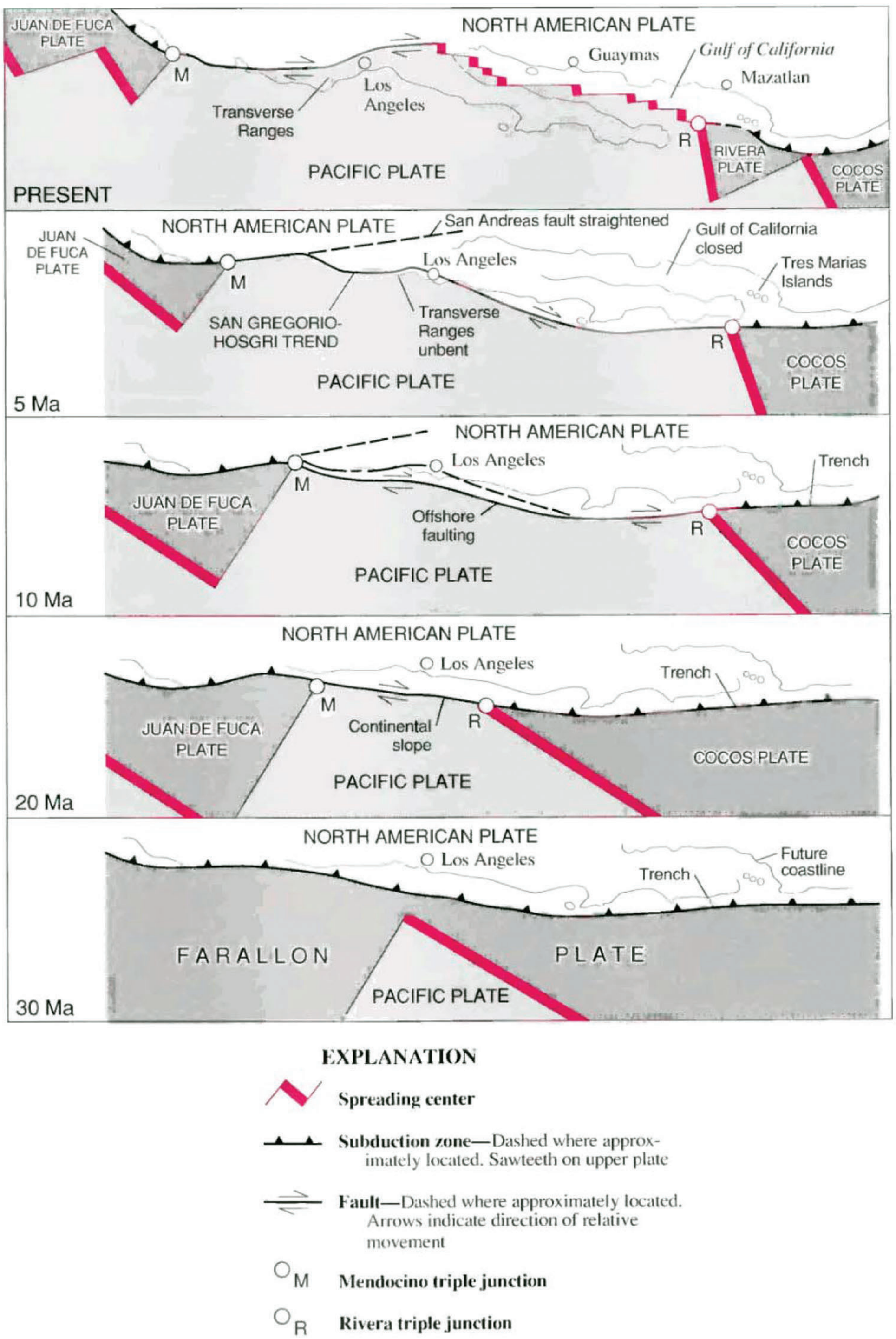

Figure 4.2. Maps showing evolution of the San Andreas transform fault system (from Irwin, 1990).

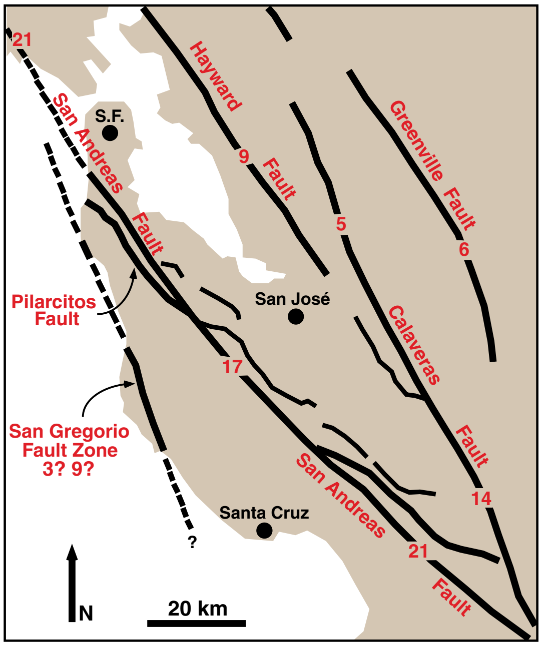

Figure 4.3. Faults of the San Andreas system in the San Francisco (S.F.) Bay area. Average slip rates shown are current estimates in mm/yr based on a wide range of geodetic (primarily GPS) and geologic (stream offset, trench) studies (after Kelson and others, 1992).

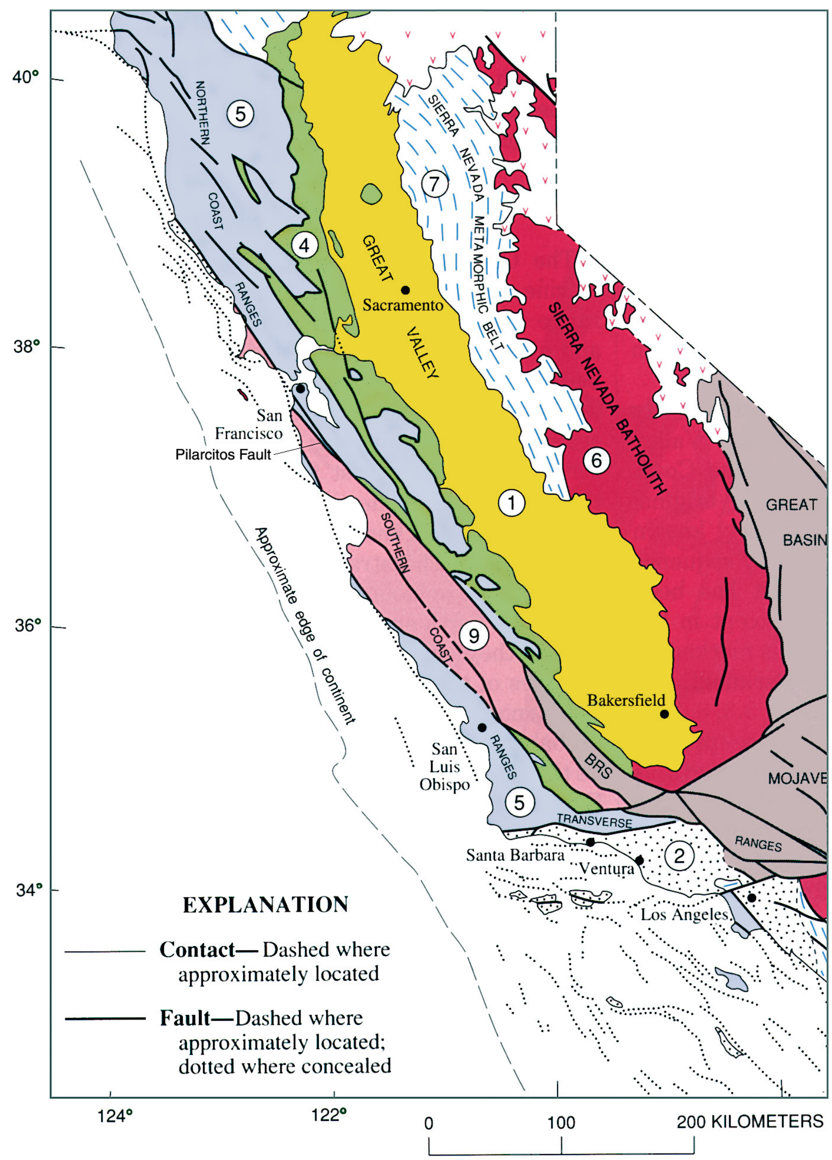

Figure 4.4. Simplified geologic map of part of California, showing distribution of principal basement rock groups (modified from Irwin, 1990). Units shown are (1) Quaternary alluvium, shown only in the Great Valley, (2) area in which older rocks are concealed by overlying Upper Cretaceous and Tertiary deposits, (4) Great Valley sequence of forearc-basin sedimentary rocks, (5) Franciscan Complex, (6) Sierra Nevada granitic batholith, (7) Sierran metamorphic belt intruded by Sierran granitic rocks, and (9) Salinian block.

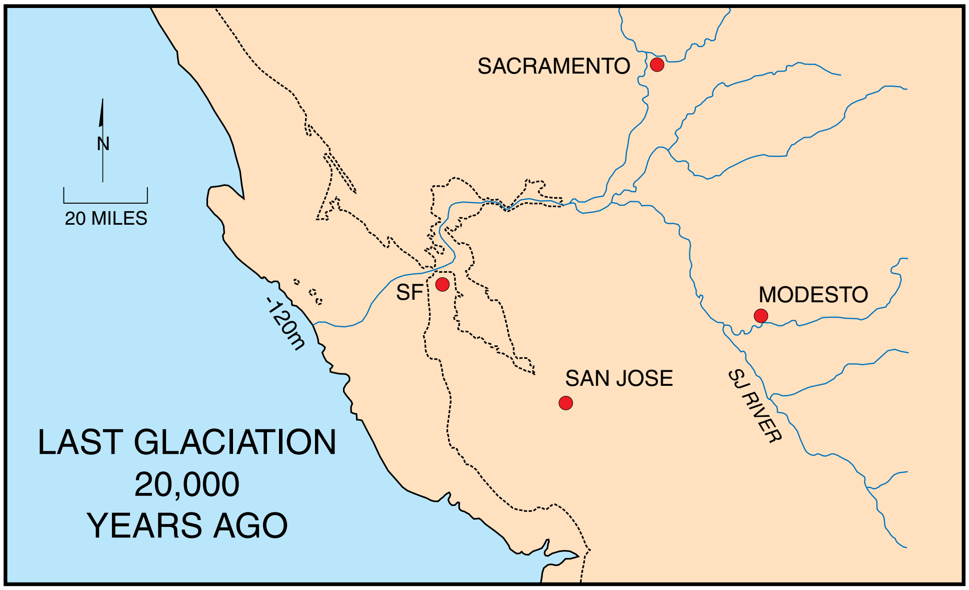

Figure 4.5. Map of the San Francisco Bay area at 20 ka, during the last major glacial period. The coastline was close to the present 120-m bathymetric contour, and areas to the east were exposed above sea level. The present coastline is dashed, including the outlines of the Farallon Islands west of San Francisco (SF). Figure by K.R. Lajoie, U.S. Geological Survey.

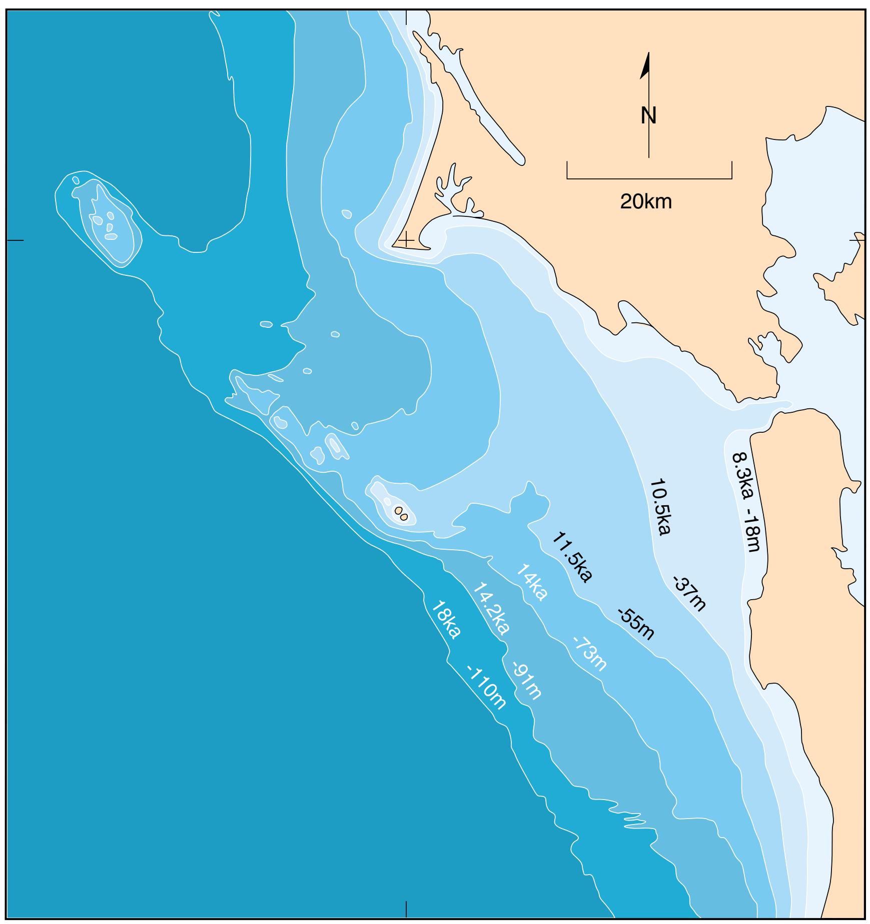

Figure 4.6. The rise of the ocean level on the continental shelf after the last major global glaciation, from ~18 ka until ~8 ka. A long stillstand of sea level occurred during this rise at about 11.5 ka, as indicated by widespread, thick, nearshore deposits of gravel and sand presently at ~55 m depth. Figure by K.R. Lajoie, U.S. Geological Survey.

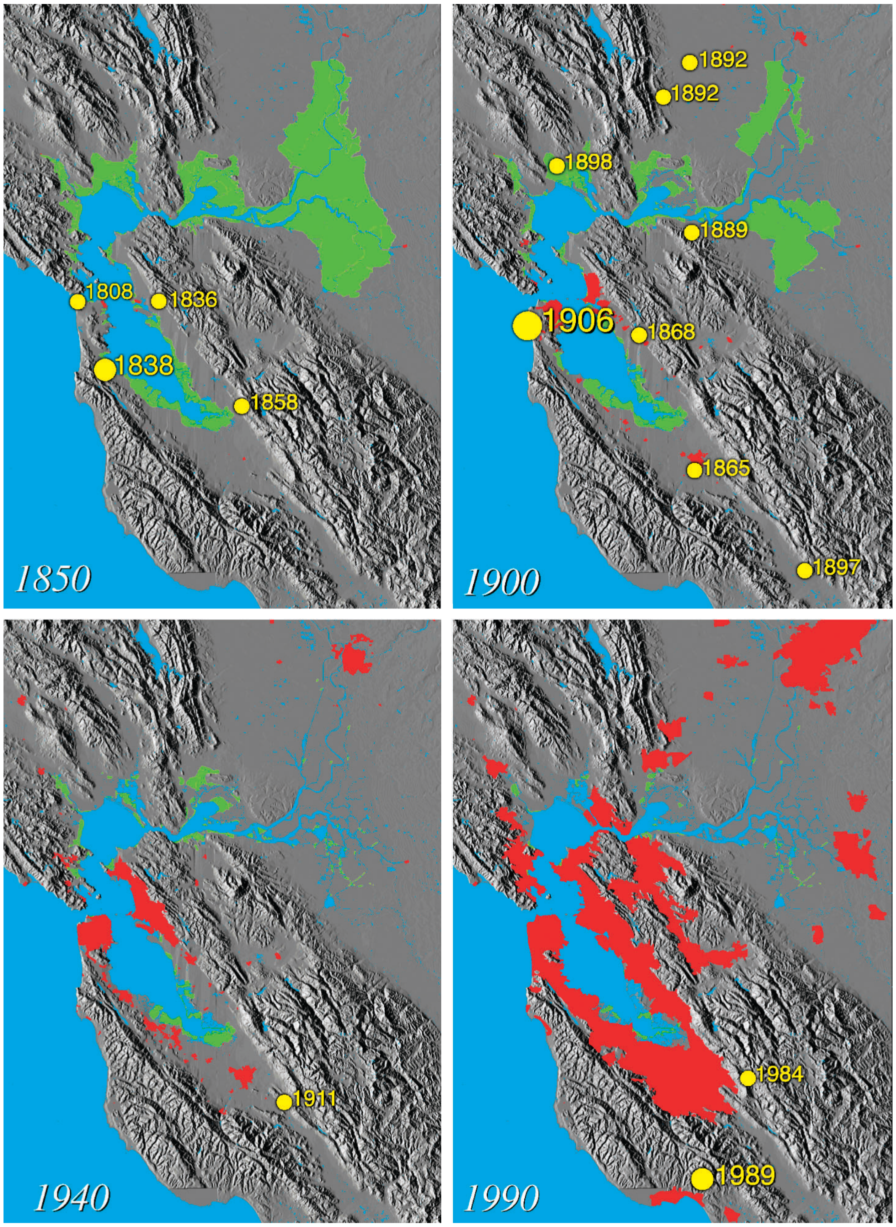

Figure 4.7. Effect of human activity and population growth in the San Francisco Bay area during the period from 1850 to 1990. The green pattern shows open wetlands, and the red pattern shows growing population centers. Also shown are some of the major earthquakes (yellow dots) that have taken place in the Bay area during historical time (from Len Gaydos, U.S. Geological Survey).

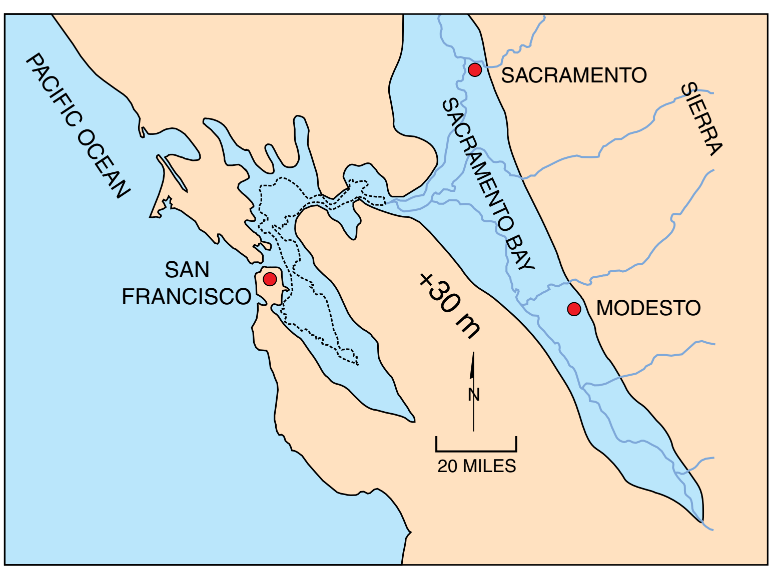

Figure 4.8. Extent of flooding by rising sea level if greenhouse warming continues unabated, and approximately one third of the world's volume of land-bound ice and snow melts (not sea ice). The resulting rise would put sea level at about 30 m above the present sea level. Dashed line shows approximate outline of the present San Francisco Bay. Figure by K.R. Lajoie, U.S. Geological Survey.

Figure 4.9. A portion of the geologic map of the San Francisco-San José quadrangle (Wagner and others, 1990), showing field-trip route and stops.

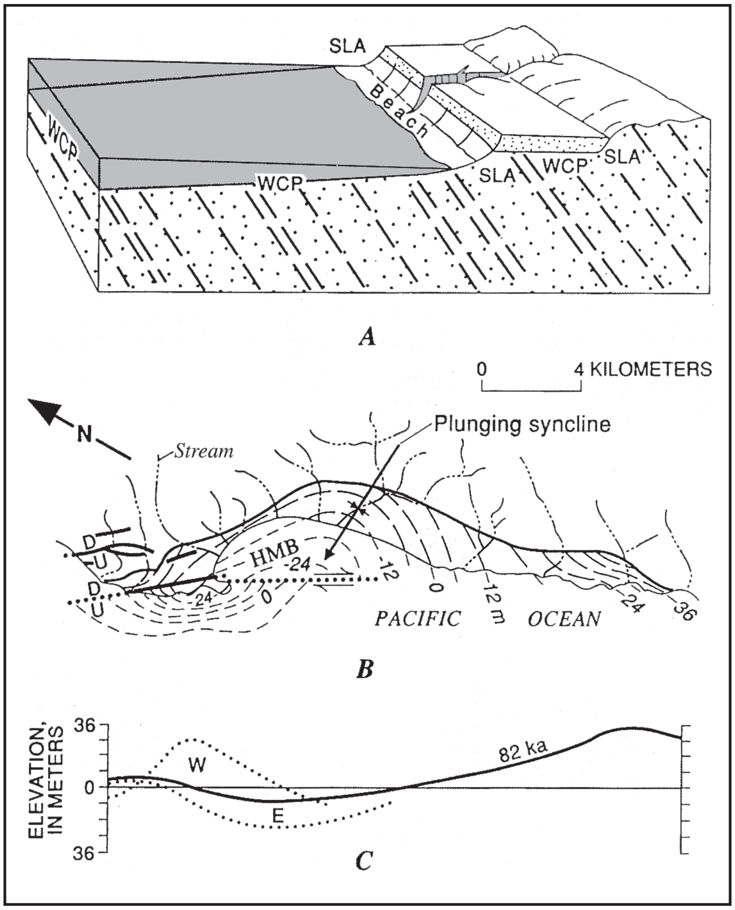

Figure 4.10. Local variability in coastal uplift shown by deformed shoreline angle and wave-cut platform. ***A,*** Coastal geomorphic features used to measure Quaternary deformation. SLA, shoreline angle; WCP, wave-cut platform; WCP' and SLA', elevated surface and shoreline angle of an older wave-cut platform mantled by sediment (stippled). ***B,*** Deformed Pleistocene wave-cut platform at Half Moon Bay (HMB) showing structure contours in meters. Arrows on fault indicate direction of relative movement. U, upthrown side; D, downthrown side. ***C,*** Platform profiles on fault plane (dotted lines: E, east; W, west), showing vertical separation across fault and deformation relative to shoreline angle (heavy line). Modified from Lajoie (1986).

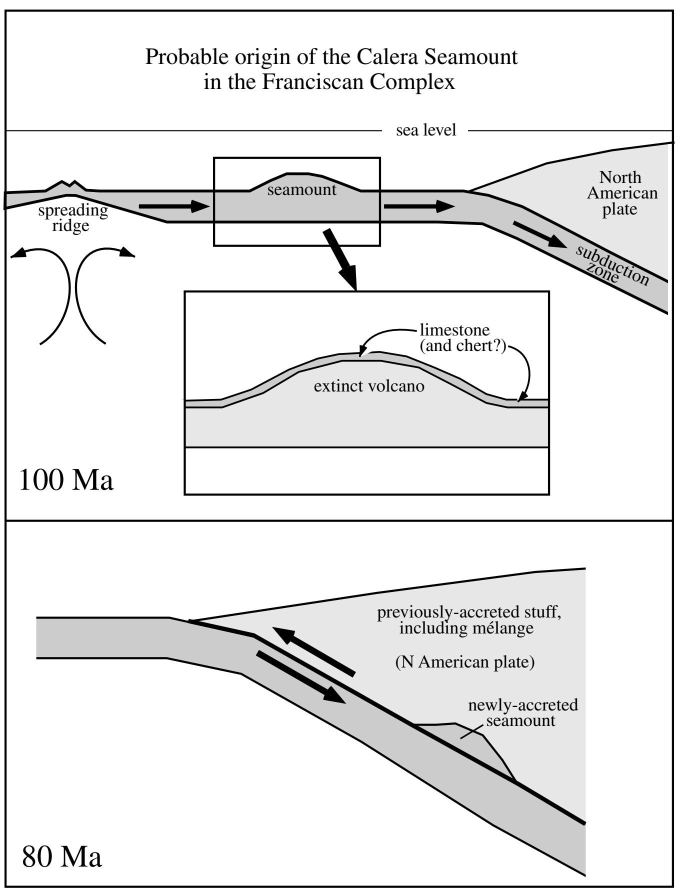

Figure 4.11. Cross-sections showing probable origin of the Calera Seamount in the Franciscan Complex

Figure 4.12. Aerial view looking south along San Francisco Peninsula showing road repairs after the March 22, 1957, earthquake. The photograph, taken in April 1957, shows equipment clearing landslide debris north of Woods Gulch. Photo courtesy of California Division of Highways, as reproduced by Sullivan (1975).