Geology of the Golden Gate Headlands

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Introduction

This field trip focuses on the rocks of the peninsular headlands found just north and south of the Golden Gate, on lands of the Golden Gate National Recreation Area. Exposed in dramatic seacliffs, these rocks not only form a spectacular backdrop for the Golden Gate Bridge, but also provide a detailed geologic record of Pacific Basin and active continental margin processes going back 200 million years. This is arguably one of the longest records of its type in the world. The significance of these rocks, however, goes beyond the geologic history that they tell, for they, and others of the Franciscan Complex associated with them, played a critical role in developing our current understanding of subduction zone mechanics and processes. Although the serpentine of the headlands, and its relationship to mountain building, was recognized as early as 1821 (see VanderHoof, 1951; Wahrhaftig, 1984a), it was not until the late 1970's to early 1980's that these rocks were understood in the light of modern tectonic concepts. This led to the publication of the volume edited by Blake (1984), which placed the Franciscan Complex into a modern plate tectonic framework. A detailed chronology of these geologic advances is provided by Wahrhaftig (1984a).

The following article draws heavily upon the many excellent publications that the late Clyde Wahrhaftig wrote on the rocks of the San Francisco area, both for the professional geologist and the general public (for example, Wahrhaftig, 1984a, 1984b; Wahrhaftig and Murchey, 1987; Wahrhaftig and Sloan, 1989). In this paper, I will describe the characteristics of the rocks and geologic processes observed at the six field trip stops, interpret their geologic story, and place them into a regional geologic context. The primary focus will be on geology of the Franciscan Complex, but other aspects, such as the Quaternary geology and the relationship between the geology and the plant communities, will be discussed.

During the field trip, please keep in mind that the sites we are visiting all lie within a national park and that sample collecting of any kind is prohibited. Please leave your rock hammers at home, but be sure to bring your camera—the rocks are beautifully photogenic at many places.

Geologic Setting

Transform Faulting (Stop 1)

San Francisco and the Golden Gate headlands are located on the boundary between two of the Earth's great tectonic plates, the North American and Pacific Plates. Today, this plate boundary is a transform fault (the plates are sliding past each other) and is formed by what is perhaps the best-known geologic feature of California, the San Andreas Fault Zone. Movement, totaling about 1 inch (2.5 cm) a year, along the San Andreas and its subsidiary faults, the Hayward and Calavaras (fig. 3.1), is infamous for producing the large earthquakes that periodically rock California and also is responsible for the area's youthful and beautifully rugged terrain. Major earthquakes occur several times each century on these or less well-known faults in the San Francisco Bay area, releasing strain built up between the creeping plates.

In the San Francisco Bay area, the current mountains of the California Coast Ranges, the Santa Cruz Mountains and the Diablo Range, started to uplift only about 3 to 4 million years ago (Page, 1989), when pressure increased across the plate boundary due to a slight shift in relative plate motions (Cox and Engebretsen, 1985); this same shift caused the Isthmus of Panama to rise from the sea and connect North and South America. The Santa Cruz Mountains are forming where the San Andreas Fault makes a slight bend to the left. This bend produces compression, folding and thrust faulting at the plate boundary, as the Pacific Plate tries to slide northward past the North American Plate. In contrast, valleys between the ranges, such as the San Francisco Bay/Santa Clara Valley, lie in stable or slowly downdropping areas formed between the major faults, in this case the San Andreas, Hayward and Calavaras Faults (fig. 3.1) (Page, 1989).

Right lateral movement on the San Andreas Fault system may be responsible for a major structural break developed under the Golden Gate Straits (Wakabayashi, 1999). This tectonic feature is indicated by a dramatic shift in the direction that the strata and thrust planes dip on opposite sides of the Golden Gate, from northeasterly on the San Francisco Peninsula to southerly in the Marin Headlands (fig. 3.2). Based on structural and paleomagnetic evidence, the Marin Headlands have undergone 130 degrees of clockwise rotation (Curry and others, 1984). The timing of this rotation is poorly constrained, but it postdates emplacement and folding of Franciscan Complex rocks in the area and is likely the result of transform tectonics.

Making San Francisco Bay

Although the valley in which San Francisco Bay resides probably began to form 2 to 3 million years ago, when the surrounding mountains and hills started to rise on either side, the first known estuarine (marine influenced) rocks were laid down only about 600,000 years ago, as dated by the Rockland ash bed which overlies the earliest marine rocks (Sarna-Wojcicki; personal commun., 2001). Cores taken during bridge-foundation studies and construction record up to seven different estuarine periods over the past half million years, corresponding to times of high sea level during interglacial periods (Atwater, and others, 1977; Sloan, 1989). During the glacial periods, when vast quantities of ocean water were stored in continental glaciers, the Bay floor became a valley and experienced erosion and downcutting. At those times, the huge, glacial-fed ancestral Sacramento River flowed through the Bay valley and out the Golden Gate Straits. Ocean water started flooding into the present San Francisco Bay only about 8,000 years ago, when the sea reentered the Golden Gate following the last glaciation (Wisconsin).

The Franciscan Complex (Stops 2 to 6)

The San Andreas Fault system is a relatively new geologic feature in the San Francisco Bay area, originating to the south 28 million years ago, but extending through the Bay area only 6 to10 million years ago (Page and Wahrhaftig, 1989). In contrast, older rocks of coastal California indicate that, before the Pacific Plate started slipping northward past the North American Plate on the San Andreas Fault system, the Pacific Ocean floor was subducted (moved) beneath the western edge of the North American Plate (fig. 3.3). The distinctive rocks of the world-famous Franciscan Complex, named at San Francisco and underlying much of coastal northern California, formed in this subduction zone.

In the Bay area, rocks of the Franciscan Complex form the basement for the Coast Ranges east of the San Andreas Fault. The Franciscan primarily consists of graywacke sandstone and argillite, but also contains lessor amounts of greenstone (altered submarine basalt), radiolarian ribbon chert, limestone, serpentinite (altered mantle material), and a variety of high-grade metamorphic rocks such as blueschist (high-pressure), amphibolite, and eclogite (high-temperature). These rocks are typically highly fractured and disrupted and may be mixed together on a local scale to create what is called a *mélange* (French for “mixture” or “blend”).

Franciscan Complex rocks in the Bay area range in age from about 200 to 80 million years old. They represent an accretionary wedge, a complex body of rock that accumulates in a subduction zone. The Franciscan Complex is composed of an amalgamation of semicoherent blocks, called tectonostratigraphic terranes, that were episodically scraped from the subducting oceanic plate, thrust eastward, and shingled against the western margin of North America (fig. 3.3). This process formed a stacking sequence in which the structurally highest rocks (on the east) are the oldest, and in which each major thrust wedge to the west becomes younger. Within each of the terrane blocks, however, the rocks become younger upsection, but the sequence may be repeated multiple times by thrust faults.

Franciscan Terranes in the Bay Area

Franciscan terranes are composed of oceanic rocks that may include igneous basement material and marine sedimentary rocks. Zones of mélange separate the terranes. In the Bay area, the Franciscan Complex is divided into the eastern and the central belts, with the older eastern belt lying structurally higher and being of higher metamorphic grade than the central belt (Blake and others, 1984). This field trip will focus on central-belt rocks, which Blake and others (1984) divided into eight terranes in the Bay area (fig. 3.2). This division is based on differences in basement types and ages, in the age and types of overlying sedimentary sequences, and in their metamorphic grade.

San Francisco and the Marin Headlands contain three of these terranes, from oldest to youngest, the Alcatraz, Marin Headlands, and San Bruno Mountain. Separating the terranes are the Hunters Point and City College mélange zones, which are primarily composed of sheared serpentinite and shale with scattered blocks of greenstone, chert, graywacke, and high-grade metamorphics (fig. 3.2). The Alcatraz terrane is characterized by graywacke turbidite deposits containing fossils indicating that the sediments were deposited between 130 and 140 million years ago (Early Cretaceous) (Blake and others, 1984, Elder, 1998). The Marin Headlands terrane, which is discussed in more detail below, contains an oceanic sequence including basaltic crust covered by open-ocean chert deposits and overlying continental-derived sandstone. Fossils in these units indicate that the chert was deposited from about 200 million to 100 million years ago (Early Jurassic to Late Cretaceous) and the sandstone between 100 and 90 million years ago (Murchey and Jones, 1984). The San Bruno Mountain terrane is composed predominately of sandstone and has yielded no fossils. Although its age is unknown, the block is thought to be Late Cretaceous in age, based on its position west of the Marin Headlands terrane (fig. 3.2).

Marin Headlands Terrane

On this field trip, we will be looking at rocks of the Marin Headlands terrane and the Hunters Point mélange zone, which bounds it to the east (figs. 3.2, 3.4, 3.5). The thick sequence of rocks preserved in the Marin Headlands terrane has received much attention by geologists in the last few decades, yielding a detailed record of their transport history (fig. 3.6). Tropical fossils and paleomagnetic evidence indicate that the terrane originated in the central Pacific near the equator. It then moved northeastward with the oceanic plate towards the North American Plate, finally colliding with North America at the latitude of today's Mexico (Murchey, 1984; Murchey and Jones, 1984). After this oceanic fragment became attached to the North American margin, rather than being subducted under it, right-lateral faulting produced by northeasterly directed subduction transported it northward along the western edge of the continent. Finally, San Andreas-related transform faulting moved it farther up the coast to the Bay area and rotated the Marin Headlands block into the position the we find it in today (Wahrhaftig 1984a; Curry and others, 1984; Wakabayashi, 1999). The following discussion of rock types and field trip stops will fill in the details of how scientists deciphered this story from the rocks.

Franciscan Rock Types

Basalt (Stop 2)

Basalt makes up about 20 to 25 percent of the exposed rocks of the Marin Headlands terrane. Alteration of Franciscan Complex basalt, presumably by hot seawater circulating through it at the mid-ocean ridge, has resulted in low-grade metamorphism and the development of the minerals chlorite and pumpellyite. These minerals give the basalt a dark green color and hence its common name, *greenstone*. Basalt in the Marin Headlands is typically deeply weathered, forming a zone of orange-brown clays and iron oxides that extends to depths of 5 to 10 m (15 to 30 feet). Most roadcuts do not penetrate this weathered zone to expose fresh rock. When subjected to constant wave action, however, the basalt forms hard, erosion-resistant black to dark green seacliffs like those seen at the Point Bonita.

Most basalt of the Marin Headlands terrane exhibits well-developed pillow forms and is vesicular. A few flows lack internal structure and may represent submarine flood basalts. Tuff and volcanic breccia beds also are present at some localities including Point Bonita.

Typical pillows are a few tens of centimeters to a meter across. They have rounded tops and downward projecting keels that were molded by the tops of the older underlying pillows. These forms provide an upsection indicator and demonstrate an underwater origin for the flows (Moore, 1975). When seen in cross section, some pillows show thin layers of basalt alternating with thicker quartz and calcite layers. These internal features resulted from lava partially draining out of the pillows to form voids that were later filled by quartz and calcite. The thin lava shelves in the pillows coincide with the true horizontal at the time of the flow, providing an accurate paleohorizontal indicator (Moore and Charlton, 1984).

At some places, such as near the tunnel entrance out to Point Bonita lighthouse and near Battery 129, chert can be seen between the pillows (fig. 3.7). Near Battery 129 and at the south end of Rodeo Beach, cream to pink pelagic limestone also is present. The occurrence of these relatively slowly deposited sedimentary rocks indicates periods of volcanic quiescence between pillow lava flows. In addition, the presence of limestone between the pillows demonstrates that the mid-ocean ridge crest was above carbonate compensation depth (CCD), which in today's oceans is typically around 4 km depth, allowing carbonate to be preserved. The lack of limestone in the immediately overlying chert sequence shows that the cooling oceanic plate descended below CCD shortly after it moved away from the ridge crest.

Chemical analysis of the basalts of the Marin Headlands terrane indicates that they are rich in titanium and iron, which is consistent with a mid-ocean ridge basalt (MORB) origin, particularly at a spreading center near a hot spot. However, at Point Bonita, the basalt chemistry is somewhat different, suggesting a seamount or oceanic island site of eruption, although a mid-ocean ridge site near a hot spot is also possible (Wahrhaftig and Wakabayashi, 1989; Shervais, 1989). The difference in composition between the Point Bonita basalt and that elsewhere in the Marin Headlands terrane led Wahrhaftig and Wakabayashi (1989) to establish a separate Point Bonita block.

Chert (Stop 3)

Chert underlies about 50 percent of the Marin Headlands and a small part of the Presidio. Because chert is resistant to weathering, it forms many of the ridge tops. At places, the chert is found in depositional contact with the underlying basalt (fig. 3.8; Battery 129) or with the overlying clastic rocks (Alexander Avenue), but most contacts are formed by faults. The chert is bedded and is composed predominately of 2- to 10-cm thick red chert layers that alternate with thinner, dark-red shale beds. The red color indicates the oxidized state of the iron in this siliceous rock. Light green to white chert beds also are present, but are much less common and occur in the mid to upper parts of the section. In general, the bedding thickness decreases and the shale content increases upsection. Because of the prominent thin bedding, these rocks are commonly called ribbon chert. Chert lying near the basalt contact has a silvery gray to black manganese-oxide staining. This manganese is probably related to both hydrothermal and hydrogenous Mn associated with the spreading ridge (Karl, 1984).

Locally, the chert is intensely folded, forming complex sharp-crested chevron and isoclinal folds (fig. 3.9). Such folding is well exposed along Conzelman Road. Most likely, the folding occurred when the Marin Headlands terrane was wedged against the continental margin and subsequently faulted to its present position. However, abrupt changes from only slightly deformed sequences to highly folded areas, and unbroken sharply folded beds, have led to speculation that some of the contorted folding reflects submarine slumping on the flank of the mid-ocean ridge prior to final hardening of the layers (Bailey and others, 1964; Wahrhaftig, 1984a).

The chert of the Marin Headlands contains abundant radiolarian fossils that are silt to sand size and that are clearly visible with a hand lens. These tiny siliceous fossil shells provided much of the silica content in these beds. The radiolaria can be extracted from the rock with hydroflouric acid, providing spectacular three-dimensional fossils (fig. 3.10). By studying these fossils, Murchey (1984) determined that the oldest cherts deposited on the basalt contain species that lived about 200 million years ago (Early Jurassic, Pliensbachian Stage) and that the youngest species, at the top of the section near the sandstones, lived about 100 million years ago (Cretaceous, Albian to Cenomanian stages). The chert sequence, therefore, reflects 100 million years of pelagic deposition and is one of the longest stratigraphic sequences of chert in the world (Wahrhaftig and Murchey, 1987).

The cherts contain a number of features indicating that they formed in the equatorial central Pacific (fig. 3.6). Murchey's (1984) study identified radiolarians characteristic of warm tropical to subtropical waters. This finding, coupled with the fact that red, oxidized radiolarian cherts are typically associated with high productivity upwelling zones found just north and south of the equator (Karl, 1984), suggest that the sediments forming these rocks were deposited in near the equator. The observed upsection decrease in bedding thickness also is consistent with a depositional site that was moving northward, out of the equatorial high-productivity zone, thus resulting in progressively thinner bedding cycles (Karl, 1984). The general lack of terrigenous, continental-derived sediments throughout the sequence implies that it was deposited far offshore, probably more than 1,000 km (600 miles), if there was no topographic barrier to impede continental sediment supply (Karl, 1984).

The prominent rhythmic bedding of the cherts is one of their most distinguishing features (fig. 3.11). The contrast between the hard chert beds and the intervening shale beds has been magnified by diagenesis following deposition. Subtle original compositional differences would have been enhanced as silica moved from the less silica-rich zones to the more silica-rich beds during diagenesis, in which opal-A silica from radiolarian shells was transformed into opal-CT silica, and ultimately to quartz (Tada, 1991).

However, the origin of the primary compositional differences is debatable. Karl (1984) concluded that the bedding was produced by periodic submarine landslides (dilute turbidity currents) that occurred on the flank of the mid-ocean ridge. Predominately lenticular bedding and some internal sedimentary features are consistent with this origin. Alternatively, the rhythmic bedding may represent periodic changes in oceanic upwelling and siliceous productivity, possibly developed in response to the Earth's orbital cycles (Decker, 1991). A growing body of literature indicates that the Earth's 21,000, 41,000 and 100,000 year orbital cycles, as well as others, are reflected in biogenic sedimentary sequences (Fischer, 1991). In any case, diagenesis would have enhanced the cycles produced by either turbidite or productivity mechanisms.

Clastic Rocks—Conglomerate, Sandstone, Shale (Stops 4 and 6)

Continentally derived clastic rocks underlie about 25 percent of the Marin Headlands terrane. The clastic rocks weather deeply and are usually exposed only in the coastal bluffs, where they erode to form steep, dangerous cliffs. This trip will visit two good sandstone exposures, one at the north end of Rodeo Beach and the other at the north end of Baker Beach (fig. 3.12). Sandstone is dominant among the clastic rocks and is mainly a lithic arkose wacke, consisting of a poorly sorted mixture of angular plagioclase feldspar, quartz, and volcanic rock fragments. The volcanic component gives the sandstone its characteristic greenish-gray color. This "dirty sandstone" is commonly called graywacke, and is typical of submarine landslide deposits (turbidites) associated with subduction zones along continental margins.

The sandstone intervals are composed of beds typically ranging in thickness from 1 to 2 m to more the 20 m. The beds generally show no internal features other than graded bedding, although internal laminae or cross-bedding are occasionally present. The base of the beds may be pebbly or have small shale and other rock clasts. Beds grade upward to progressively finer sandstone and may be capped by thin shale intervals, usually no more than 10 to 20 cm in thickness.

This grading from cobbles or pebbles at the base to fine sand and silt at the top of beds results from decreasing transport energy after a slide event. As the energy decreased, smaller and smaller particles drop out of suspension and are deposited. Most sandstone beds reflect the A, C, and D facies of the classic Bouma turbidite sequence (Bouma, 1962) with the preservation of the pelagic E facies at the tops of some (Wahrhaftig, 1984b). Locally, carbonized plant material is apparently concentrated at the tops of sandstone beds, perhaps floating to the top of the sand slurry following a turbidite event.

Shale intervals are typically less than 50 cm thick and reflect periods of pelagic deposition between turbidite events. Rarely, shale intervals several meters in thickness are present, such as immediately above the chert sequence on Alexander Avenue. Portions of the mélange at north Baker Beach appear to contain much shale, but the highly disturbed nature of the outcrop prohibits determination of bed thickness.

Conglomerate is rare but has been identified at three localities on the Marin Headlands—two localities at Bonita Cove and one on Wolf Ridge (Wahrhaftig, 1984a). No conglomerate will be seen on this field trip. The two Bonita Cove localities have different compositions: one contains greenstone, limestone, and red chert pebbles, and the other locality has gray quartzite and chert cobbles.

The sandstone of the Marin Headlands terrane has yielded two molluscan fossils, both ammonites (fig. 3.13). One was found near the base of the north tower of the Golden Gate Bridge and identified by Hertlein (1956), and the other came from the south end of Baker Beach and was reported on by Schlocker and others (1954). These Cretaceous ammonites provide quite accurate ages of early Cenomanian and early Albian for the clastic rocks north and south of the Golden Gate, respectively (Elder, 1998). These ages are consistent with the radiolarian-derived Albian to Cenomanian age for the top of the underlying chert sequence. These ammonites lived widely throughout the Pacific and thus provide no evidence regarding the latitude at which the rocks were deposited.

Serpentinite (Stop 5)

Serpentinite is associated with the mélange blocks of the central belt that surround the Marine Headlands terrane (fig. 3.2). Highly fractured serpentinite rocks and associated mélange form hills with broad crests and abundant slumps and landslides. Although serpentinite does not typically form sizable outcrops, soils form slowly over serpentinite, such that disturbed areas may be barren for extended periods before vegetation develops. The bluffs above north Baker Beach provide spectacular serpentinite exposures that also exhibit the landslides and seeps characteristic of this rock type (fig. 3.14).

Serpentinites are rocks composed of the serpentine-group minerals, chrysotile (asbestos), lizardite, and antigorite. These minerals impart a characteristic blue-green color to the serpentinite blocks and the sheared clay zones surrounding them. In outcrop, massive rounded serpentinite blocks, typically 1 to 2 m in diameter, are surrounded by a matrix of sheared, flaky serpentine, called slickentite. The massive blocks may show relict porphyritic textures (bastite replacements of pyroxene) of deep oceanic crust and mantle rocks (dunite and harzburgite). Other blocks may contain a lacy network of 1-5 mm thick asbestos veins (fig. 3.15).

The serpentinites of the Franciscan Complex in the San Francisco Bay area are exotic fragments of oceanic crust and mantle (ophiolite) that were accreted to the active continental margin rather than being subducted under it (Coleman, 1989). Hydrothermal activity in the subduction zone has completely altered the mineralogy of these deep crust and mantle rocks to serpentinite, making them much lighter and more plastic. These serpentinites are probably derived from the base of the Coast Range Ophiolite, a piece of Middle Jurassic oceanic crust that underlies the rocks of the Great Valley Sequence of central California. Extensive faulting, and possibly upward diapiric movement of these relatively light rocks, has led to their ascent to the Earth's surface.

Because serpentinite is altered mantle rock, its chemistry is unlike that of most other continental rocks. Serpentinite is low in potassium and calcium, which are important plant nutrients. It also contains high levels of magnesium, nickel, and chromium that are potentially toxic to plants. Therefore, plants living on serpentine soils are specially adapted to these unusual chemical conditions, and serpentine areas can often be mapped by using the abrupt vegetation change that occurs at their boundaries.

Serpentinite outcrops in California and throughout the world are known to support rare and endangered plant species (Kruckenberg, 1984). Some species are confined to just one or a few outcrop areas. Eight of the twelve rare plants found at the Presidio grow on serpentinite, including the federally endangered Presidio clarkia and Raven's manzanita, the latter of which is represented by a single plant (fig. 3.16).

Quaternary Geology of the Colma Formation (Stop 6)

The Pleistocene Colma Formation locally forms a thin veneer over rocks of the Franciscan Complex on the Golden Gate headlands of San Francisco Peninsula. The formation extends to Angel Island and to the southern peninsula, where it overlies the Pliocene and Pleistocene Merced Formation from Fort Funston, south (Schlocker, 1974). The Colma Formation is mostly composed of sandy deposits laid down from 80 to 125 thousand years ago during an interglacial period (Sangamonian/Mindel-Riss/Holsteinian Interglacial) when sea level was slightly higher than today. At that time, northern San Francisco Peninsula was an island separated from the southern peninsula by the narrow"Colma Strait" (fig. 3.17).

The predominately poorly consolidated sands of the Colma probably originated in a variety of environments ranging from shallow bay to dune and valley slopes. The formation extends under the San Francisco Bay and is developed up to 500 feet above sea level (Schlocker, 1974). It apparently represents shallow bay deposits below about 200 feet in elevation and valley-slope debris above. The permeable sands of the Colma Formation form a good aquifer, and springs are common at the interface between the Colma Formation and the underlying Franciscan Complex serpentinite at the Presidio.

Holocene Sand Dunes (Stop 6)

Holocene sand dunes mantle the Colma Formation and the Franciscan Complex over large areas of San Francisco (fig. 3.18). These dunes are composed of sand that has blown up and over the hills from Ocean Beach and Baker Beach. The sand probably originated on the broad coastal plain of the Sacramento/San Joaquin River system, which extended from the Golden Gate to the Farallon Islands during the last glacial period (Wisconsin), when sea level was about 100 m (300 ft) lower than at present (Atwater, 1979; Sloan, 1989). Sand from this plain was transported onto the beaches and blown over the coastal hills during the rapid sea level rise that occurred between about 18,000 and 5,000 years ago. Sea level has been relatively stable for the past 5,000 years, rising only 1 to 2 mm/year during that period (Atwater, 1979).

The Holocene sand dunes of this area formed one of the most extensive coastal dune systems on the West Coast, underlying about one-third of San Francisco. The dynamic nature of these dunes, constantly shifting and in different phases of ecological succession, produced a complex mosaic of sandy habitats that once supported many different plant and animal species. Today, only a small remnant of that ancient ecosystem survives, much of it within the Presidio. Preserved and restored dune habitat at Baker Beach (Stop 6) and in more inland areas, such as nearby Lobos Creek Valley, supports a much greater biodiversity than the surrounding urban areas. The coastal dune scrub community here provides food and shelter for insects, reptiles, birds, and mammals and includes several rare plants, such as the Dune gilia and San Francisco lessingia (fig. 3.16).

Road Log

The field trip begins at the National Park Service Visitor Center at the Presidio. The trip crosses the Golden Gate Bridge to stops in the Marin Headlands and then returns south to the Presidio. Figures 3.4 and 3.5 show the location of stops.

Mileage/Notes

0 From National Park Service Visitor Center drive south on Montgomery.

0.1 Turn right on Sheridan Avenue.

0.4 Sheridan Avenue becomes Lincoln Boulevard; continue on Lincoln west.

0.9 Go under Highway 101.

1.3 Turn right on Armistead; immediate left onto Golden Gate Bridge approach; then right onto the bridge.

3.3 Exit right to Vista Point at the north end of the Golden Gate Bridge.

STOP 1—Vista Point provides excellent panoramic views of San Francisco Bay, the Golden Gate Bridge and the Marin Headlands (fig. 3.4). As you stand at the Vista Point, try to visualize what this scene looked like a mere 12,000 years ago, when a rushing, glacially fed river flowed through the grand valley before you, now occupied by bay water. The river flowed through Raccoon Straits, between Angel Island and the Tiburon Peninsula, and out through the gorge of the Golden Gate before crossing a wide coastal plain to the Pacific.

Today San Francisco and the Golden Gate Bridge dominate this view. Built over a 4 year period, the Golden Gate Bridge was completed in 1937. Bridging the Golden Gate was not only one of the greatest engineering efforts of the century, it also acted as a social and economic catalyst that forever changed the San Francisco Bay region. Today more than 40 million vehicles cross the bridge each year. The foundations of the bridge towers extend 110 feet below the water into bedrock. The south tower is anchored in fractured serpentinite rock, leading to some concern about its integrity during a large earthquake.

3.5 Leave vista point onto Highway 101 north.

3.7 Exit immediately onto Alexander Avenue.

3.8 Proceed toward Sausalito on Alexander Avenue.

3.9 Turn left toward Marin Headlands (this is Bunker Road, but there is no sign).

4.1 Proceed through tunnel. The traffic light can last up to 5 minutes.

4.9 First visible chert outcrops are on the left; views encompass coastal scrub plant community typical of the Marin Headlands. No trees are native to this area; the natural landscape contains low, tundra-like vegetation due to the persistent winds and cool foggy conditions.

6.6 Turn left on Field Road.

6.9 Graywacke outcrops are visible on left.

7.0 Nike missile museum is on right.

7.7 Point Bonita Trailhead parking area is on the left (will stop here in a few minutes).

8.0 Lookout vista. From this point you can see Bird Island (covered with white guano), Point Bonita Lighthouse, basalt seacliffs and gun emplacements from the early 20th century.

8.2 Return to Point Bonita Trailhead parking area.

STOP 2—Proceed down Point Bonita Trail to locked tunnel. This stop will be focused on the pillow basalts (now altered to greenstone) of the Point Bonita block (fig. 3.4). On the way down the trail, the first outcrop seen to your right is graywacke sandstone. A prominent fault and sheared zone can then be seen separating the graywacke from greenstone. Greenstone is the predominate rock the rest of the way to the tunnel, except for a small interval of serpentinite and shale just beyond the fault. Near the tunnel entrance, well-developed pillows are seen in the basalt of the cliff face. Pods of red chert, altered to jasper, are present between some pillows (fig. 3.7). The chert was deposited during periods between eruptions. Locally, in the Marin Headlands terrane, interpillow limestone pods also are found, indicating that the sea floor was above calcium carbonate compensation depth (CCD) for at least a short time after forming. The best pillows are seen near the water line below Point Bonita lighthouse, where the waves have beautifully exposed them. The tunnel to the lighthouse is open on weekends and Mondays between 12:30 and 3:30 p.m. The red-looking growth covering the basalt by the tunnel entrance is a type of cyanobacteria (Trentepohlia). Feral cabbage, escaped from the lighthouse keeper's garden, is a common plant here, as well as a many native species, such as cobweb thistle and blue-dicks.

Return to the bus.

9.2 Return and turn left onto Bunker Road toward Rodeo Beach.

9.6 Pull out into gravel parking area just beyond large warehouse building.

STOP 3—This abandoned quarry face provides excellent exposures of the radiolarian ribbon cherts characteristic of the Marin Headlands terrane (fig. 3.4). The chert seen here displays dark steely-gray manganese staining typically developed in rocks near the base of the chert section, probably reflecting manganese-rich hydrothermal and bottom waters associated with the mid-ocean ridge volcanism. Complex folding is well displayed on the left-hand side of the cliff face, probably produced when the terrane was accreted onto North America (fig. 3.19). Thrust faults formed during the period of accretion have sliced the oceanic sequence up and repeated it ten or more times in the headlands area (Wahrhaftig, 1984a). Prominent chert and shale bedding rhythms also are evident (fig. 3.11). These sedimentary cycles, which have been enhanced by burial diagenesis, reflect either submarine landslides or cyclic changes in radiolaria productivity and (or) clay input. The shells of some radiolaria (fig. 3.10) can be seen on freshly broken surfaces with a handlens.

9.6 Proceed left and on to Fort Chronkhite.

10.2 Proceed to the bus parking at Rodeo Beach at north end of parking area.

STOP 4—From the Rodeo Beach parking lot (fig. 3.4) proceed west onto the gated road and then left, up the path to the cliff top. From the top of this promontory are excellent views of the coast to the north and south. The bluffs in this area are composed of graywacke sandstone. The deep cove just to the north cuts into an area of less resistant, more shaley turbidite beds.

To the south and east, Rodeo Cove and Rodeo Lagoon are visible (fig. 3.20). No other West Coast beaches have the composition or coarse grain size of the beach in Rodeo Cove. The beach is composed predominately of rounded red and green chert and lesser amounts of mafic volcanic rock fragments that fall mostly in the 1 to 4 mm grain size range (Wakeley, 1970). In addition to the brightly colored chert pebbles, the beach contains carnelians, semitranslucent orange chalcedony, that formed in the vesicles of the nearby pillow basalts.

Rodeo lagoon fills a valley drowned by recent sea-level rise following the last glacial period. The lagoon is developed behind a barrier bar formed by the beach. During winter storms, ocean water may overtop the bar during storm tides and high seas, forming landward-dipping washover fans. In addition, rains may increase freshwater flow into the lagoon, causing overtopping and erosion from the landward side (Hill, 1970). The barrier beach reforms during summer dry season conditions, when the coastal beaches build up and out.

Leave Rodeo beach and proceed eastward.

12.4 Turn on to McCullough Road.

13.1 A small slump can be seen on the left.

13.2 Ahead on left, note large graywacke blocks on top of the chert outcrops.

13.3 Turn left onto Conzelman Road.

13.7 Stop bus for great view of folds in chert on left, bay and bridge views on right.

14.0 Manganese stained chert can be seen on left; similar to Stop 3 (above).

14.1 Pillow basalts crop out on left, and contact with overlying chert is visible.

14.5 Take entrance ramp to Highway 101 South, and onto Golden Gate Bridge. Stay in far right lane.

16.5 Turn right on Merchant Road immediately after toll booth.

16.7 Turn right on Lincoln Boulevard.

16.72 Take immediate right on Langdon Court and proceed to bus parking.

STOP 5—From the Coastal Overlook (fig. 3.5) we will walk to the beach where we will examine serpentinite and mélange outcrops. This is a clothing optional public beach that provides excellent exposures. Take the trail from the southwest corner of the parking lot (fig. 3.5, loc. 1), over the bluff edge and into the trees. Spectacular exposures of serpentinite can be seen in the large landslide headwall as the trail descends the bluff (fig. 3.5, loc. 2). The steep coastal bluffs in this area are formed from a series of these landslide headwalls (fig. 3.14). East dipping foliation and flattening of the boulders can be seen in these exposures.

Just south of where the trail meets the beach, a rock promontory juts into the ocean (fig. 3.5, loc. 3). The north side of this exposure is serpentinite and the south is composed of sandstone. This fault contact juxtaposes the large serpentinite block forming the bluffs to the north, against a mélange zone developed to the south at the boundary of the Marin Headlands terrane and the Hunters Point mélange zone (fig. 3.2).

Climb over the promontory and walk south across the low wetlands area formed at the toe of the landslide. A serpentine seep 100 m (320 ft) inland feeds these wetlands. Several rare plants in the area, including the Franciscan thistle (fig. 3.16), are adapted to, and largely restricted to, serpentine seep conditions. Proceed to the edge of the low bluff to the west (fig. 3.5, loc. 4). Here, the bluff is composed of green clay that appears to be slowly oozing onto the beach. The clay contains popcorn-like balls of what may be zeolite minerals (fig. 3.21) and is thought to be an altered volcanic tuff bed, similar to tuffs found in mélange throughout the central and northern Coast Ranges (Wahrhaftig and Sloan, 1989).

Continue south to the large ribbon-chert outcrop at the end of the beach. This chert block is in fault contact with a large sandstone block to the south (we will inspect this block at Stop 6) and a pillow basalt block to the north (fig. 3.22). These blocks are pieces of the Marin Headlands terrane and probably represent the northern boundary of that terrane on the San Francisco Peninsula.

Head back north and, if time permits, continue past the trailhead about 250 m (800 ft) to the north end of the beach, where large rocks extend into the water (fig. 3.5, loc. 6). These are high-grade metamorphic rocks composed of amphibolite. Locally they are garnet-bearing and have textures suggestive of partial melting indicative of high-temperature metamorphism (about 700°C; Wakabayashi, 1999). Quartz- and garnet-rich beds appear to be metachert, probably metamorphosed during the early stages of subduction (Wakabayashi, 1999). High-grade metamorphic blocks of the Franciscan Complex all date to about 160 million years ago, but the Hunters Point mélange zone is probably not older than about 100 million years, based on the age of the Marin Headlands terrane to its west (Wakabayashi, 1999).

Return up the trail to the bus.

17.0 Exit parking lot and turn right onto Lincoln Boulevard.

17.3 Serpentine chaparral restoration site containing last remaining Raven's Manzanita.

17.8 Turn right on Bowley Street, then right onto Gibson Street to Baker Beach.

18.0 Turn right to Battery Chamberlin Road.

18.2 Park in bus parking area at Baker Beach.

STOP 6—From the Baker Beach parking lot, walk through Battery Chamberlin, a coastal defense gun emplacement built in 1904. The battery contains the last "operational" six-inch diameter disappearing rifle on the West Coast. Walk north to the exposures at the end of the beach. This is another clothing optional beach.

The bluffs at the north end of Baker Beach provide an excellent opportunity to observe sandy turbidite deposits of the Marin Headlands terrane close at hand (fig. 3.5, loc. 7). These graywacke sandstone bluffs are composed of massive sandstone beds as much as 5 m (26 ft) in thickness, separated by finely laminated cross-bedded sandstone and shale interbeds from 5 cm to 1 m (2 in to 3 ft) thick. Some of the interbeds contain abundant plant material, now carbonized and coaly, that apparently rose to the tops of the underwater landslide flow deposits (fig. 3.23). The abundance of plant material suggests that there was land nearby. The turbidite beds are cut by numerous small faults, and calcite veins fill many of these faults and fractures.

Walk back south to the nearby tan bluffs fig. 3.5, loc. 8). These bluffs are composed of poorly consolidated silts and sands of the Colma Formation (Pleistocene) that are dipping about 20 degrees south. The Colma Formation weathers to form badlands topography in this area (fig. 3.24). Low angle or planer laminations are evident in the basal Colma Formation exposed on the beach here and suggest a beach foreshore or backshore environment. The overlying finer-grained rocks may represent lagoonal deposits.

The top of the Colma Formation is marked by a prominent gray soil horizon that is overlain by Holocene sand dunes (fig. 3.18). In ravines along the cliff base, high-angle cross beds indicative of sand dune deposits are visible in the slightly consolidated sand present near the base of the Holocene unit (fig. 3.25). The dunes on the bluffs here provide a glimpse into what the northern San Francisco Peninsula looked like before becoming urbanized. These dunes are some of the least impacted in the city, providing critical habitat space for rare plants like Dune gilia and San Francisco wallflower (fig. 3.16).

Return to the bus at the Baker Beach parking lot.

18.4 Turn left on Gibson Street.

18.5 Turn left on Bowley Street.

18.6 Turn left on Lincoln Boulevard.

19.1 Turn right on Kobbe Street.

19.4 Continue straight on Kobbe past Upton Street.

19.7 Turn left on Park Boulevard.

19.8 Turn right on Lincoln Boulevard.

20.5 Turn right on Montgomery Street and back to William Penn Mott Jr., Visitor Center.

End of trip

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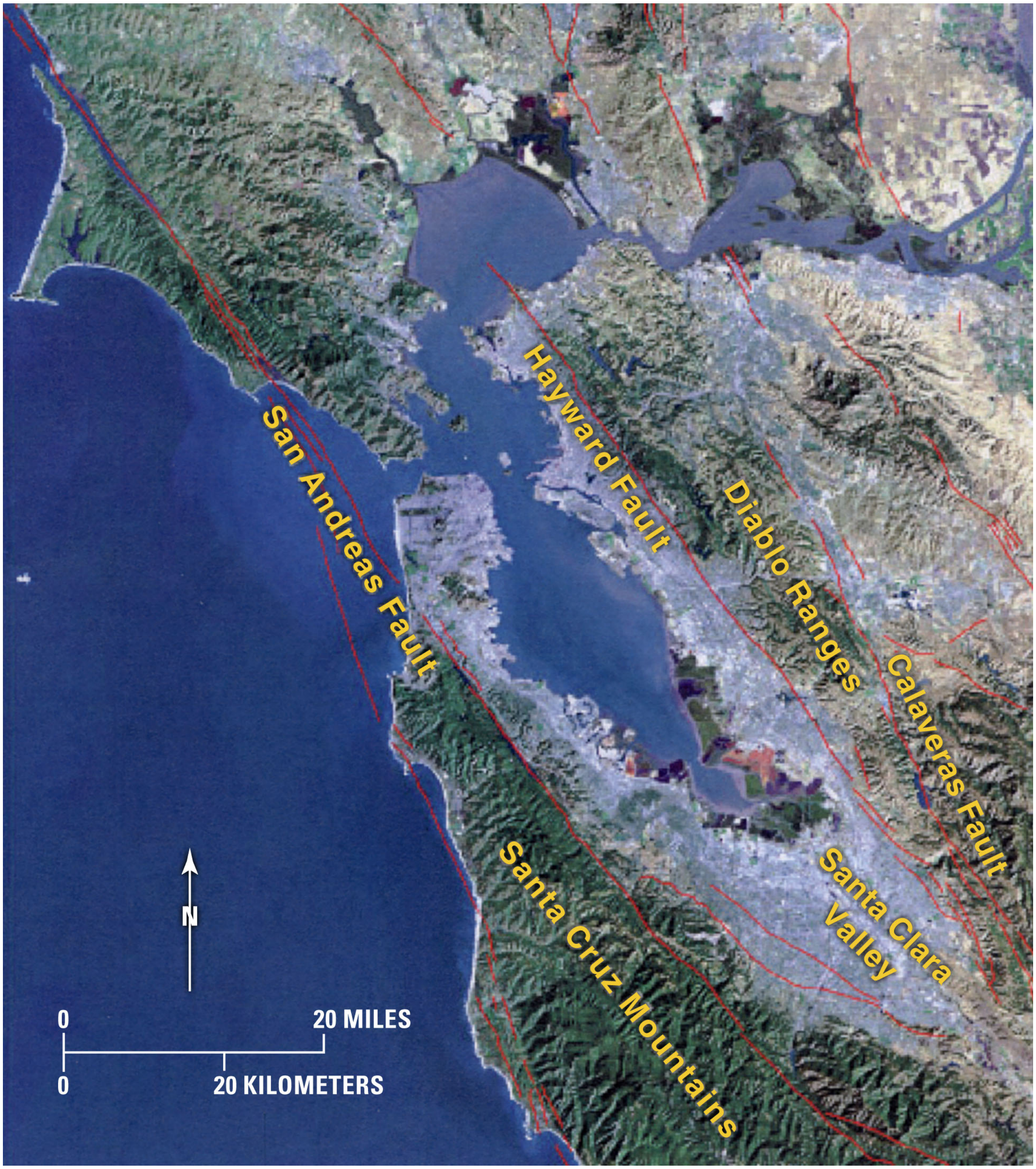

Figure 3.1. Satellite image of San Francisco Bay area showing major faults and geographic features discussed in text (modified from U.S. Geological Survey and Pacific Gas & Electric image).

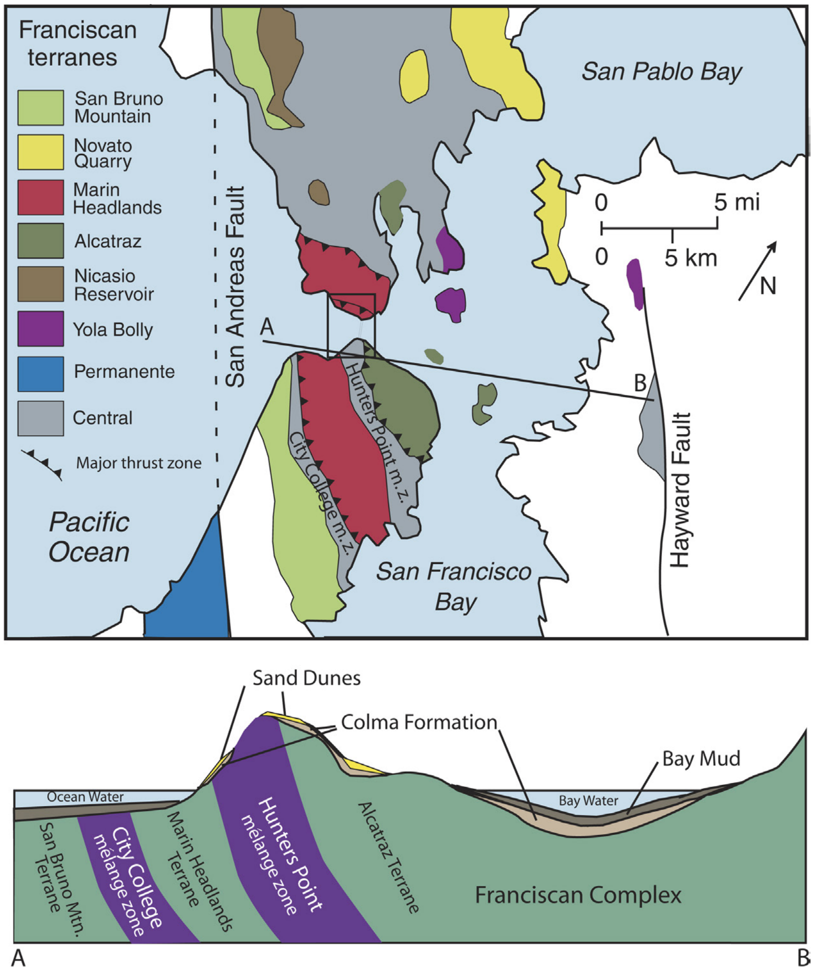

Figure 3.2. Top part of figure shows terranes of the Franciscan Complex in the San Francisco Bay area and dip direction of major thrust faults referred to in text. Cross section A-B for lower part of figure also is indicated (modified from Blake and others, 1984). Bottom part of figure is a schematic cross section through northern San Francisco Peninsula across bay to Oakland (not to scale).

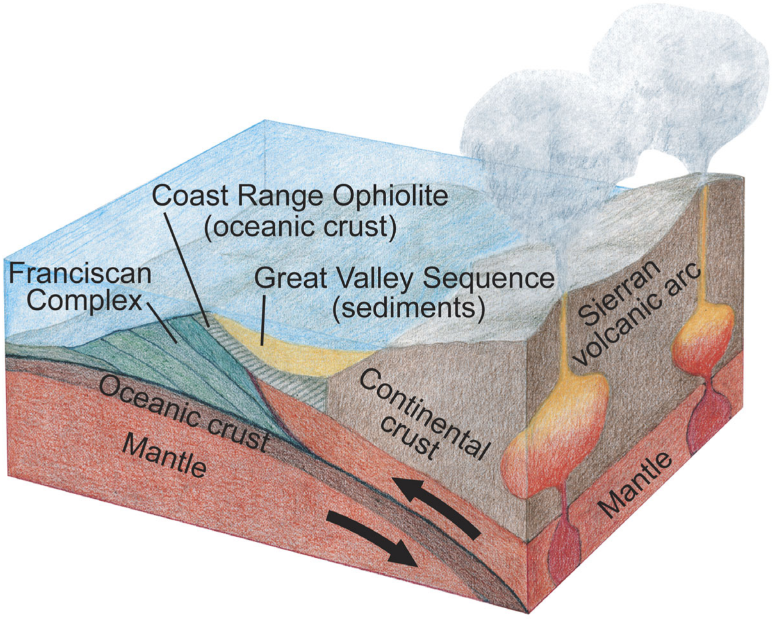

Figure 3.3. Cartoon of the subduction zone present on the West Coast 100 million years ago showing position of the accretionary wedge of the Franciscan Complex.

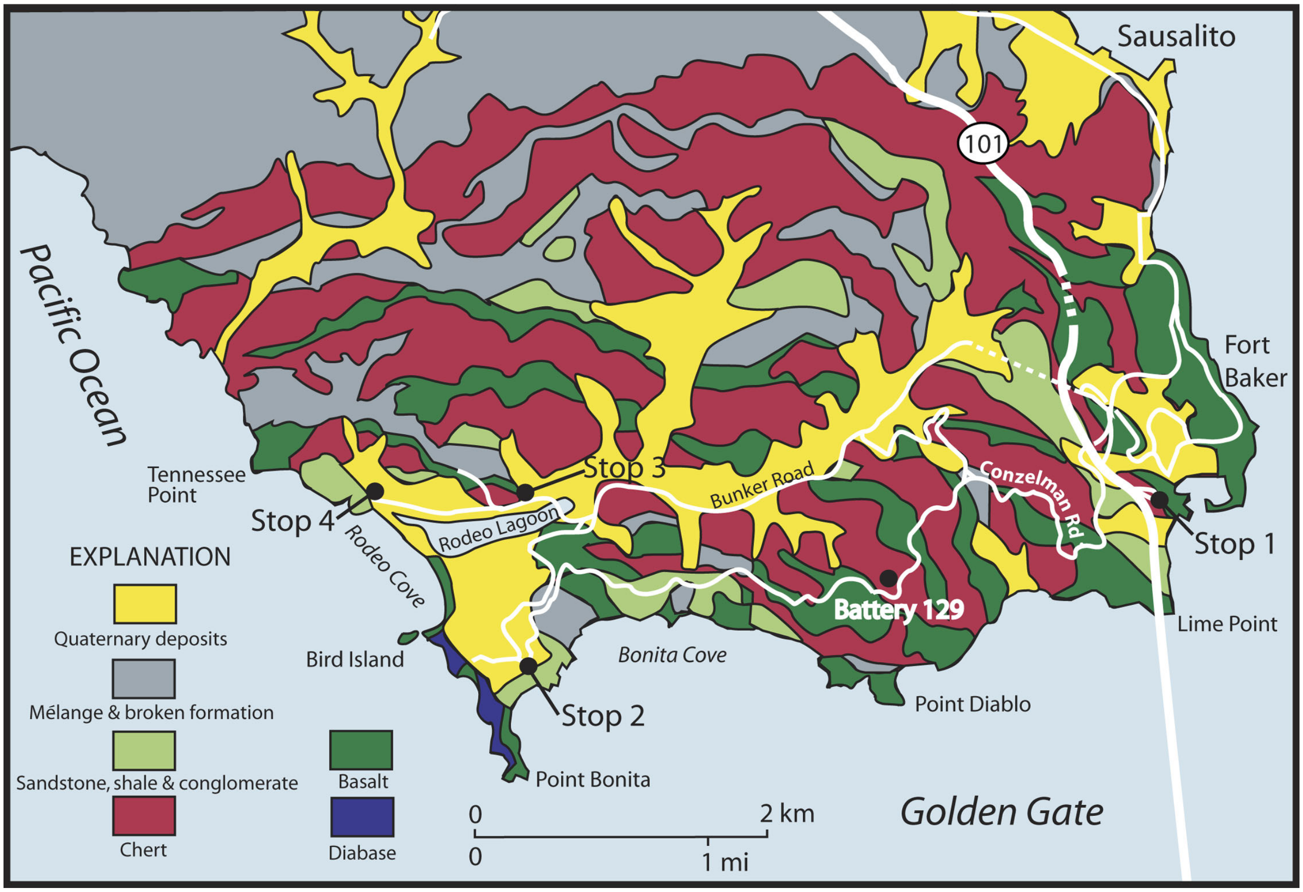

Figure 3.4. Geologic map of the Marin Headlands showing major geologic units, location of field trip stops, and other places referred to in text (modified from Wahrhaftig and Murchey, 1987).

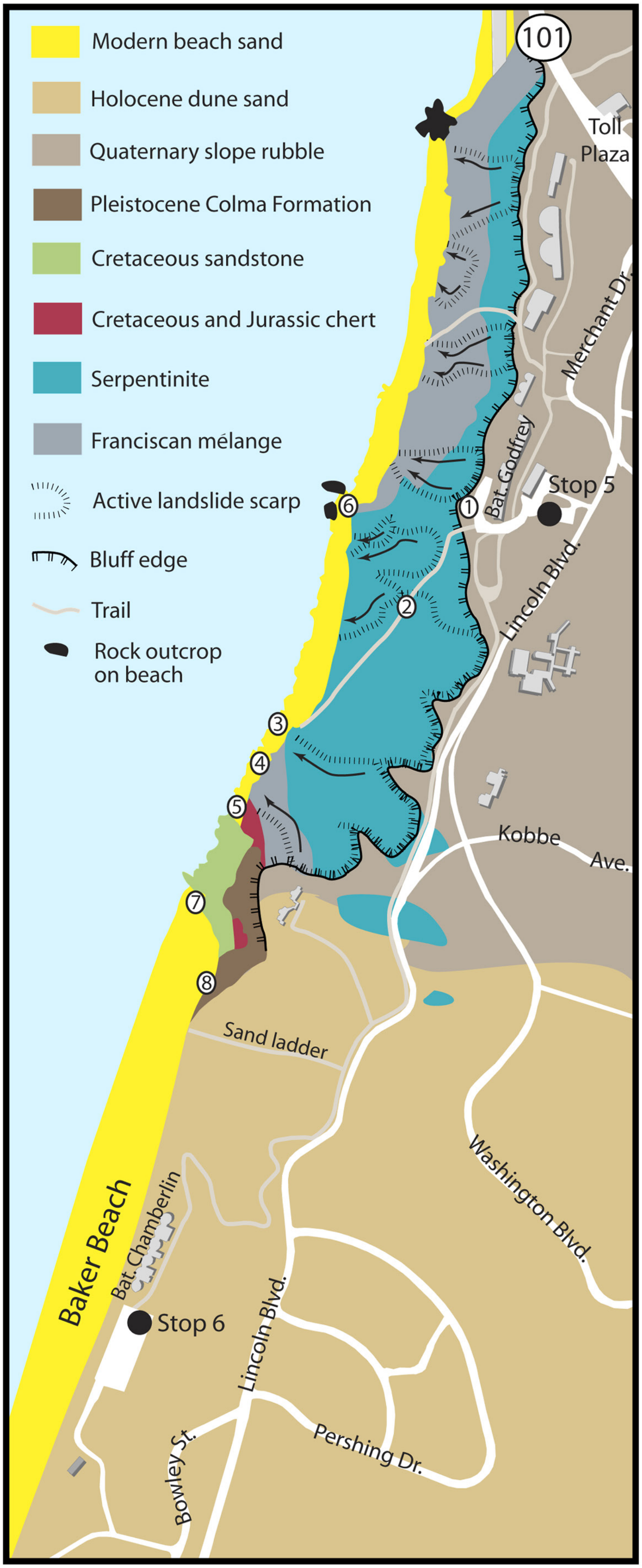

Figure 3.5. Geologic map of coastal bluffs in the Presidio showing major geologic units, location of field trip stops, and locations at stops referred to in text (modified from Wahrhaftig, 1984b; Schlocker, 1974). Arrows indicate the direction of landslide movement.

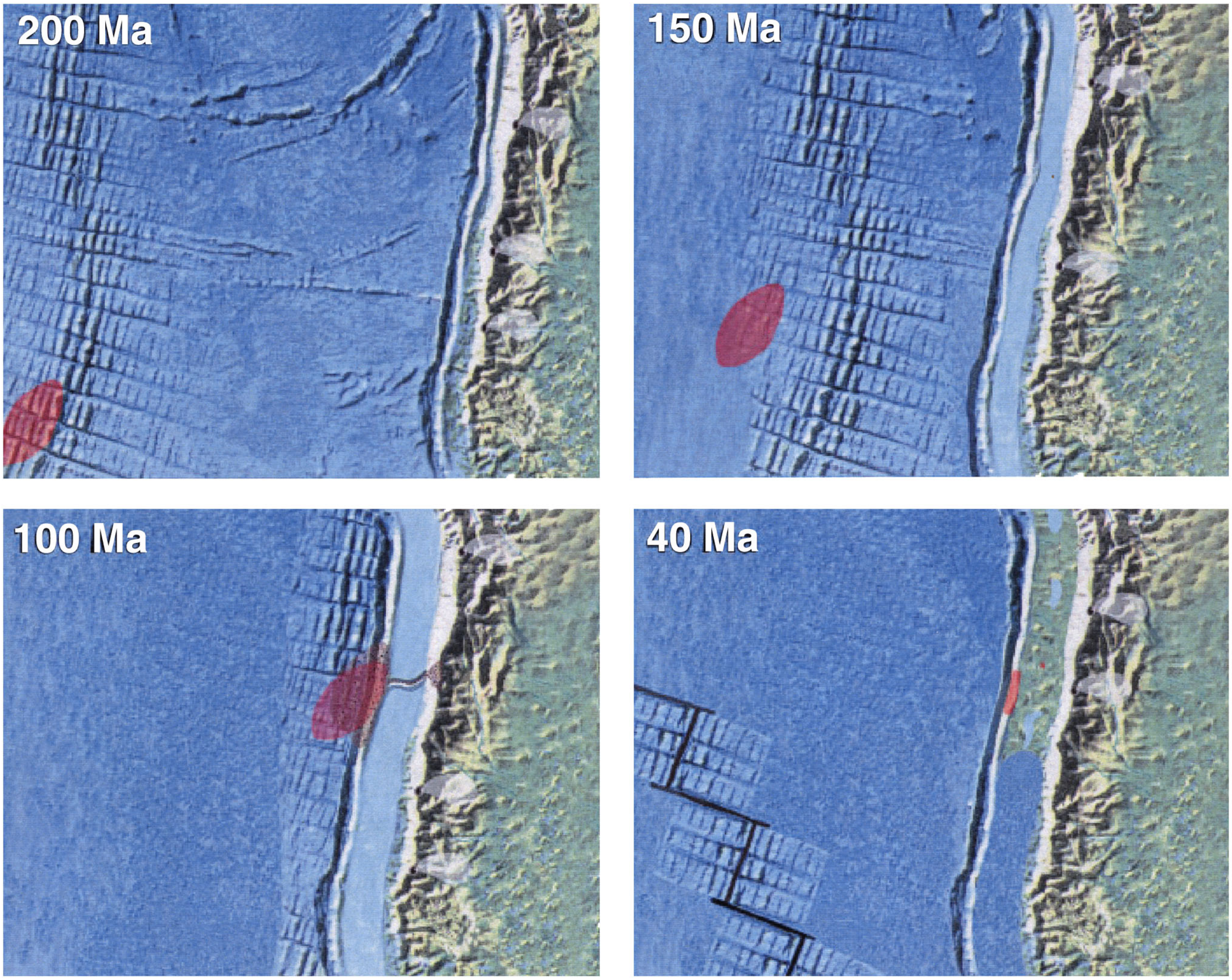

Figure 3.6. Transport history of the Marin Headlands terrane across the Pacific Basin. Panels show approximate geographic position of terrane, shown as red area, at 200, 150, 100, and 40 million years ago (modified from Murchey and Jones, 1984).

Figure 3.7. Pillow basalt with red chert interbeds at Point Bonita. Hat for scale.

Figure 3.8. Ribbon chert in depositional contact with pillow basalt at Battery 129.

Figure 3.9. Folded chert beds on Conzelman Road. Note the lack of fracturing on the tight folds. Knife for scale.

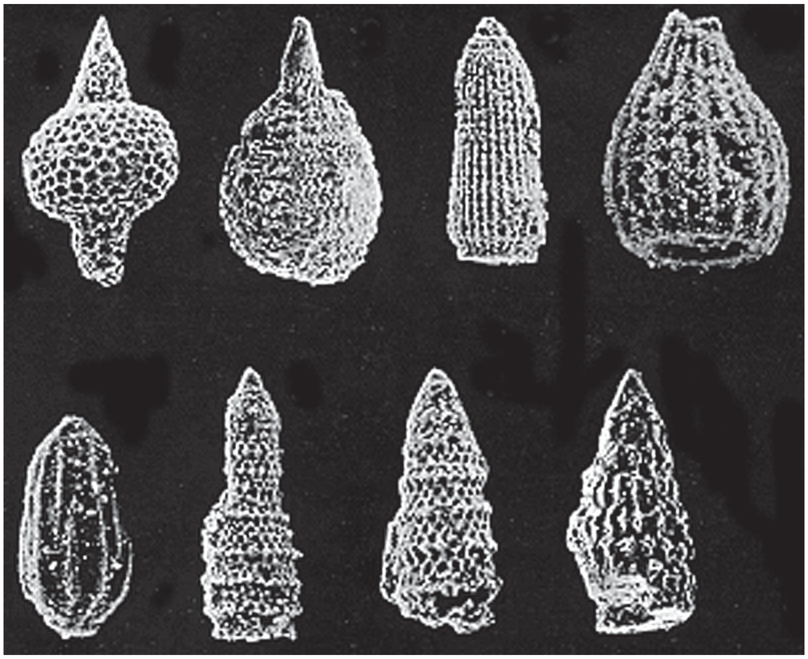

Figure 3.10. Scanning electron micrographs of silica tests (shells) of Radiolaria removed from the Marin Headlands chert by using hydroflouric acid.

Figure 3.11. Bedding rhythms developed in ribbon chert along Conzelman Road. Diagenetic transfer of silica has enhanced the bedding. Knife for scale.

Figure 3.12. Graywacke sandstone turbidite beds at the north end of Baker Beach. Note the darker fine-grained interbeds dipping northeast, away from the camera.

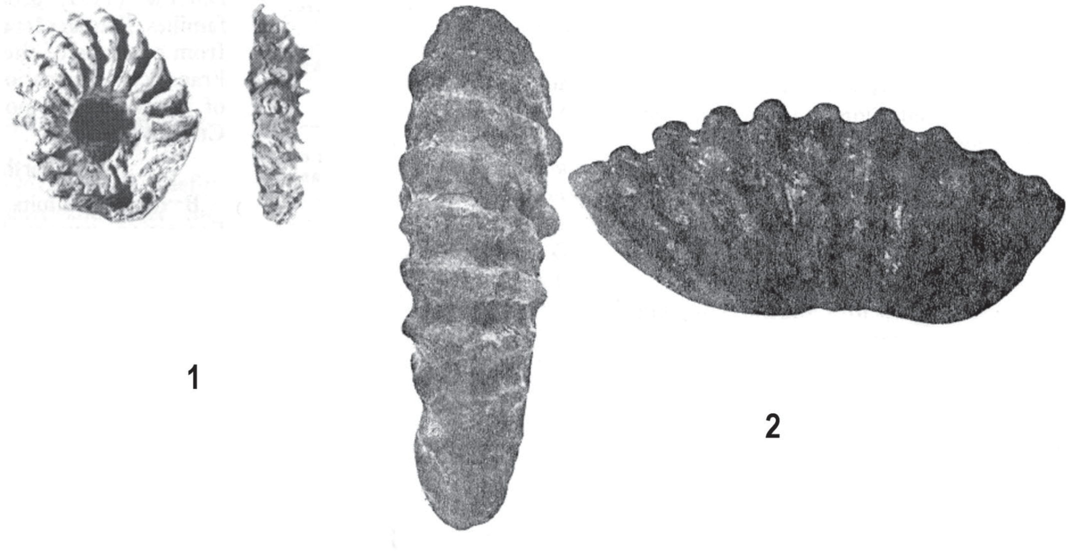

Figure 3.13. Ammonite fossils from turbidite sandstones of the Marin Headlands terrane—(1) *Douvilleiceras* cf. *mammillatum* (Schlotheim) from Baker Beach area, (2) *Mantelliceras* sp. from below the north tower of the Golden Gate Bridge (photos from Hertlein, 1956; Schlocker and others, 1954).

Figure 3.14. Serpentine exposed in landslide headwalls in bluffs of the Presidio. The dark rocks in the ocean below are high-grade metamorphic amphibolite blocks.

Figure 3.15. Lacy network of chrysotile (asbestos) veins in serpentinite boulder on the beach near the Presidio.

Figure 3.16. Rare and endangered plants living on serpentine soils and dunes of the Presidio—(1) Presidio clarkia (*Clarkia franciscana*), serpentine soils; (2) Dune gilia (*Gilia capitata*), coastal dunes; (3) San Francisco wallflower (*Erysimum franciscanum*), serpentine and dunes; (4) San Francisco lessingia (*Lessingia germanorum*), coastal dunes; (5) Raven's manzanita (*Arctostaphylos hookerii* ssp. *ravenii*), serpentine soils; and (6) Franciscan thistle (*Cirsium andrewsii*), serpentine seeps.

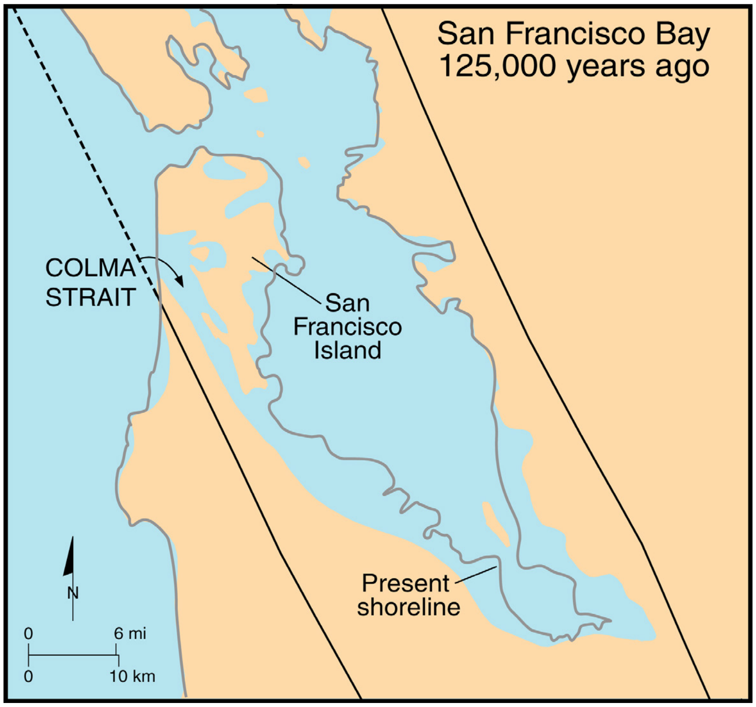

Figure 3.17. Paleogeographic map of the San Francisco Bay area when the Colma Formation was deposited about 125 thousand years ago, during an interglacial period when sea level was slightly higher than today. Note that the area of San Francisco was largely an island at that time (modified from an unpublished map based on data of Ken Lajoie, U.S. Geological Survey).

Figure 3.18. Top of Colma Formation and overlying Holocene sand dunes at Baker Beach. Note the gray soil horizon at paleoerosion surface developed between the two units.

Figure 3.19. Ribbon chert exposed in old quarry at Stop 3 of field trip. Note relatively undeformed beds on right side and folding on left.

Figure 3.20. Rodeo Beach and Lagoon. The barrier bar developed by the beach is overtopped during winter storms.

Figure 3.21. Altered tuff with zeolite nodules in Franciscan Complex mélange on beach (Stop 5, loc. 4).

Figure 3.22. Large blocks in the mélange at the boundary of Marin Headlands terrane on the beach at the Presidio (fig. 3.5, loc. 5). Greenstone blocks are in foreground, ribbon chert in center, and graywacke sandstone in background.

Figure 3.23. Turbidite sandstone with lens of carbonized plant material at the north end of Baker Beach (fig. 3.5, loc.7). Knife for scale.

Figure 3.24. Colma Formation forming small badlands in the bluffs at the north end of Baker Beach (fig. 3.5, loc.8).

Figure 3.25. High-angle crossbeds exposed in a gully in the poorly consolidated Holocene dune deposits at the north end of Baker Beach (fig. 3.5, loc.8). Knife for scale.