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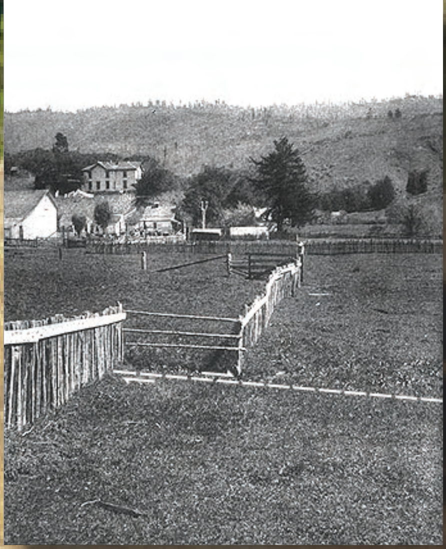
Where's the San Andreas Fault?

A Guidebook to Tracing the Fault on Public Lands in the San Francisco Bay Region

General Information Product 16



Published in commemoration of the 100th anniversary of the 1906 earthquake

U.S. Department of the Interior
U.S. Geological Survey

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By Philip W. Stoffer

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U.S. Department of the Interior
Gale A. Norton, Secretary

U.S. Geological Survey
P. Patrick Leahy, Acting Director

U.S. Geological Survey, Reston, Virginia: 2006

Available from U.S. Geological Survey Information Services
Box 25286, Denver Federal Center
Denver, CO 80225

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Cataloging-in-Publication data are on file with the Library of Congress (URL http://www.loc.gov/).

Produced in the Western Region, Menlo Park, California
Manuscript approved for publication, September 13, 2005
Text edited by James W. Hendley II
Layout and design by Stephen L. Scott

Cover—View looking southeast along the straight valley of Upper Stevens Creek. The stream valley roughly follows the trace of the San Andreas Fault in the central Santa Cruz Mountains (also see fig. 7-8). Insets show (top) the San Andreas Fault scarp at Mission San Juan Bautista, (left middle) a historical photograph of a fence in Olema offset by the 1906 earthquake, (right middle) granitic sea cliffs of the Point Reyes headlands west of the fault, and (bottom) redwood trees growing along the fault in Sanborn County Park in Santa Clara County.

Title Page—Manzanita forest grows on serpentinite in the Calero Hills east of the San Andreas Fault. Mount Umunhum and the Sierra Azul ridge are in the distance.

Foreword

April 18, 2006, will mark the 100th anniversary of the “Great San Francisco Earthquake.” On that day in 1906, the earth ruptured for about 300 miles (500 km) along the San Andreas Fault in northern California, both on land and where it extends offshore. The earthquake and fires that followed caused catastrophic damage to cities and towns throughout the San Francisco Bay region and had a dramatic impact on the culture and history of California. The event also initiated national interest in the study of earthquakes and disaster prevention.

Although the very mention of the San Andreas Fault instills concerns about great earthquakes, perhaps less thought is given to the glorious and scenic landscapes the fault has been responsible for creating. The San Andreas Fault extends across California for nearly 800 miles between its southern terminus beneath the Salton Sea to where it runs offshore at Cape Mendicino in the north. Along its path, the fault cuts through desert landscapes, grasslands, forested coastal mountain ranges, rural rangeland, and even some urban areas. Along much of its route, the fault cuts through land held in the public trust, including national parks, national forests, open-space, local parks, water districts and reservoirs, and is locally overlain by roads, bridges, dams, homes, and other manmade features.

This field guide to the San Andreas Fault in the San Francisco Bay region not only presents detailed information on the geologic diversity of the landscape but also describes aspects of the cultural history and past and ongoing land-management practices along the fault zone. The San Andreas Fault is a prominent natural landmark feature in Point Reyes National Seashore, a unit within the National Park System. National parks are observatories for the natural world, and whether it be a mountain range, volcanoes, a river canyon, or a great fault system, geology is an underlying theme for most national parks. A primary mission of the National Park Service is to provide visitors with useful information and guided interpretations about the natural and cultural history of the landscape.

The National Park Service relies on the organizations like the U.S. Geological Survey to provide scientific information to help make informed decisions and to help educate the public. This field guide is an example of collaboration between the two Federal agencies. Our hope is that this guidebook will help enrich public understanding and encourage exploration of our natural and cultural heritage.

Don Neubacher

Don Neubacher
Park Superintendent
Point Reyes National Seashore
National Park Service
Department of the Interior

Contents

Glossary

Note that words in italics are defined elsewhere in this glossary.

Accretion. The gradual addition of new land to an older continental margin. Accretion occurs where *plate tectonic* motion, through *transform faulting* or *subduction*, moves rocks formed elsewhere, such as part of a volcanic arc in the ocean, and attaches it to the continental margin. The term accretion also applies to the gradual buildup of a thick, wedge-shape accumulation of sediments, such as a delta where rivers dump large quantities of sediments into the ocean, gradual causing the shoreline to migrate seaward.

Alluvial fan. An outspread, gently sloping mass of sediment deposited by a stream where it issues out of the mouth of a narrow canyon draining from and upland area. Viewed from above, an alluvial fan typically has the shape of an open fan with the apex being at the mouth of the canyon. Alluvial fans are common in arid to semi-arid regions, but can be covered with forests in the California Coast Ranges. Alluvial fans may merge together to form an apron-like slope along the base of a mountain front.

Alluvium. A general term for unconsolidated sediments deposited by flowing water on stream channel beds, flood plains, and *alluvial fans*. The term applies to stream deposits of recent times and it does not include subaqueous deposits, such as in lakes or undersea.

Angular unconformity. An *unconformity* in which younger sediments rest upon an eroded surface of older tilted or folded rocks.

Anticline. A fold in rock strata, generally convex upward, whose core contains the stratigraphically older rocks. (Opposite of *syncline*.)

Basalt. A dark-colored *igneous* rock, commonly *extrusive* (from volcanic eruptions) and composed primarily of the minerals of calcic plagioclase and pyroxene, and sometimes olivine. Basalt is the fine-grained equivalent of *gabbro*.

Basement complex. Undifferentiated rocks, commonly *metamorphic* and *igneous* in origin, that underlie younger rocks in a region. The basement complex, or simply basement, extends downward to the base of the Earth's crust but may be bounded by faults and structures determined by drilling, *seismicity*, geophysical data, or other geologic evidence. Basement rocks are typically the oldest rocks in a region.

Batholith. A large, generally discordant mass of intrusive *igneous* rock that has more than 40 square miles (100 km^2) of surface exposure and generally extends downward into the crust to undetermined depths. Batholiths consist of *plutonic* rocks that typically formed during a period of igneous intrusion that occurred in a region over a span of thousands to millions of years.

Breccia. A coarse-grained clastic rock, composed of angular broken rock fragments held together by mineral cement or fine-grained matrix. Examples include volcanic breccia (formed by a volcanic eruption) or fault breccia (formed from broken up rock in a *fault zone*).

Beheaded stream. Streams draining across an active *strike-slip fault* trace may be captured by an adjacent stream. With loss of its water supply or a source of sediments, the older channel will remain as a beheaded stream channel as fault motion continues.

Blind thrust. A low-angle *thrust fault* that exists below the surface, typically in a valley, but is known or inferred from drilling, *seismicity*, geophysical data, or other geologic evidence.

Blueschist. A *metamorphic facies* and rock type formed from high pressure but relatively low temperatures typical at depth within the Earth's crust, such as in a *subduction zone*.

Cenozoic. The era of time spanning about 65 million years ago to the present. The term applies to rocks that formed or accumulated in that time period. The Cenozoic Era is subdivided into the *Tertiary* and *Quaternary* periods.

Chert. A hard, dense sedimentary rock, consisting chiefly of interlocking microscopic crystals of quartz and may contain opal. It has a conchoidal fracture and may occur in a variety of colors.

Coast Range Ophiolite. An assemblage of *mafic* and *ultramafic igneous* rocks of *Jurassic* to possibly *Cretaceous* age and whose origin is associated with the upper mantle and the lower oceanic crust of the ancient Farollan Plate. The Farollon Plate predates the development of the San Andreas Fault, and rocks of the Farallon Plate were either subducted or partially accreted into the crust that now makes up the Coast Ranges. The Coast Range Ophiolite is associated with *serpentinite terranes* throughout much of coastal central and northern California.

Colluvium. A general term applied to loose and incoherent surficial deposits, usually at the base of a slope and brought their chiefly by gravity.

Conglomerate. A coarse-grained *sedimentary* rock composed of rounded to subangular fragments (larger than 2 mm in diameter) set in a fine-grained matrix of sand or silt, and commonly cemented by calcium carbonate, iron oxide, silica, or hardened clay; the consolidated equivalent to gravel.

Creep. In *earthquake* terminology, creep is the slow, more or less continuous movement occurring on faults due to ongoing tectonic deformation. In *landslide* terminology, creep is slow, more or less continuous downslope movement of surface materials (mineral, rock, and soil particles) under gravitational stresses.

Cretaceous. The final period of the Mesozoic Era (after the *Jurassic* Period and before the *Tertiary* Period of the Cenozoic Era). The Cretaceous Period began about 144 million years ago and ended about 65 million years ago.

Crystalline rock. A general term for a rock consisting of minerals in an obvious crystalline state. Crystalline rocks are typically *igneous* or *metamorphic* rock that formed deep in the Earth.

Debris flow. A moving mass of rock fragments, soil, and mud in which more than half of the particles being larger than sand size (otherwise it would be a mudflow) and with 70 to 90 percent of the material consisting of sediment (the rest is water and trapped gasses). Slow debris flows may only move a few feet per year, whereas rapid ones can reach speeds greater than 100 miles per hour. Debris flows can display either turbulent or laminar flow characteristics.

Debris flood. A typically disastrous flood, intermediate between the turbid flood of a mountain stream and a *debris flow*, ranging in sediment load between 40 to 70 percent (the rest is water and trapped gasses).

Deflected drainage. A stream that displays offset by relatively recent movement along a *strike-slip fault*. Fault motion and characteristics of the bedrock adjacent to and within a fault zone can influence erosion patterns and diversion of stream drainages over time.

Dip. The angle that a rock layer or any planar feature makes with the horizontal, measured perpendicular to the *strike* and in a vertical plane**.**

Dip-slip faults. Inclined fractures where the blocks have mostly shifted vertically. If the rock mass above an inclined fault moves down, the fault is termed *normal*, whereas if the rock above the *fault* moves up, the fault is termed *reverse*. A reverse fault in which the fault plane is inclined at an angle equal to or less than 45° is called a *thrust fault***.**

Earthquake. Ground shaking caused by a sudden movement on a *fault* or by volcanic disturbance.

Earthquake fault. An active *fault* that has a history of producing *earthquakes* or is considered to have a potential of producing damaging earthquakes on the basis of observable evidence. Not all faults are active or are considered earthquake faults.

Epicenter. The point on the Earth's surface above the point at depth in the Earth's crust where an earthquake begins.

Eolianite. A *sedimentary* rock formed from the accumulation of wind-blown sand, silt, and dust. Sandy beach or desert dune deposits may become eolianites once they become partially or completed consolidated or cemented into rock.

Escarpment. A long, more or less continuous cliff or relatively steep slope facing in one general direction, separating two level or gently sloping surfaces, and produced by faulting or erosion.

Extrusive. *Igneous* rock that forms from the eruption of molten material at the surface. Extrusive rocks include lava flows and pyroclastic material such as volcanic ash.

Facies. A general term used to characterize the aspect and appearance of a rock unit or sedimentary deposit, usually reflecting the conditions of its origin (especially for differentiating the rock or deposit from adjacent or associated rocks). Examples include *sedimentary* (beach facies, shallow marine facies, stream facies) and *metamorphic* (*greenschist* facies or *blueshist* facies).

Fault. A fracture or crack along which two blocks of rock slide past one another. This movement may occur rapidly, in the form of an *earthquake*, or slowly, in the form of *creep*. Types of faults include *strike-slip fault*, *normal fault*, *reverse fault*, and *thrust fault*.

Fault line. The trace of a fault plane on the ground surface or other surface, such as on a sea cliff, road cut, or in a mine shaft or tunnel. A fault line is the same as fault trace. Faults lines can often be difficult to resolve from general surface observation due to cover by younger sediments, vegetation, and human-induced landscape modifications.

Fault zone. A *fault* or set of related faults that is expressed as a zone of numerous small fractures or of "*breccia*" or "fault gouge." A fault zone may be hundreds of feet wide and may locally have a complex structure.

Fault system. A collection of parallel or interconnected *faults* that display a related pattern of relative offset and activity across an entire region (for example, the San Andreas Fault system).

Fault scarp. An *escarpment* or cliff formed by a fault that reaches the Earth's surface. Most fault scarps have been modified by erosion since the faulting occurred.

Felsic. A general term for light-colored *igneous* rocks typically of continental origin and rich in quartz, feldspar and other light-colored minerals. It is a mnemonic adjective derived from "fel" (for feldspar) and "si" (for silica).

Franciscan Complex. An assemblage of rocks exposed throughout the Coast Ranges of California that consists of a mix of volcanic rocks, *chert*, shale, *greywacke* sandstone, limestone, *basalt*, and other oceanic crustal rocks that have been partially metamorphosed during their migration from place of origin in a deep ocean basin to being accreted by *plate tectonic* forces onto the west coast of North America. The name Fanciscan was first applied to bedrock of *Jurassic* and *Cretaceous* age in the San Francisco region, but the name is commonly used throughout much of coastal central and northern California.

Gabbro. A group of dark-colored, basic *intrusive igneous* rocks composed principally of calcic-plagioclase minerals (labrodorite or bytonite) and augite, and with or without olivine and orthopyroxene. It is the approximate intrusive equivalent of *basalt*.

Graben. An elongate, structurally depressed crustal area or block of crust that is bounded by *faults* on its long sides. A graben may be geomorphically expressed as a *rift valley* or *pull-apart basin*.

Granitic rocks. A general name for rocks having the appearance of granite, having a crystalline texture but not necessarily having the mineralogical composition of true granite. Most "granitic rocks" in the San Francisco Bay region are not true granites, but are usually *granodiorite*, *tonalite*, *gabbro*, or other crystalline *igneous* or *metamorphic* rocks.

Granodiorite. A group of coarse-grained, crystalline, *intrusive igneous* rocks of intermediate composition between quartz diorite and quartz monzonite, and contains quartz, feldspars, biotite, hornblende. Granodiorite is perhaps the most common variety of *granitic rock* in California's Sierra Nevada and Coast Ranges.

Graywacke. A general name for a poorly sorted, dark *sedimentary* rock ranging in texture from shale, siltstone, mudstone, sandstone, or *conglomerate*, bearing a mix of grains of quartz, feldspar, and dark rock and mineral fragments, embedded in a compact clayey matrix, and possibly displaying a slight to moderate degree of metamorphism (slate, argillite, or quartzite). Graywacke outcrops in the San Francisco Bay region locally display graded bedding and are believed to have been deposited by submarine turbidity currents (See *turbidite*).

Great Valley Sequence. A thick sequence of late Mesozoic age *sedimentary* rocks (150 to 65 million years old). These rocks consist mostly shale, sandstone, conglomerate and are exposed throughout parts of California's Coast Ranges and underlies much of the Great Valley west of the Sierra Nevada Range. The Great Valley Sequence represents sedimentary material deposited in shallow shelf to deep-sea environments along the western continental margin mostly before the development of the modern San Andreas Fault System.

Greenschist. A *metamorphic* rock that has a greenish color due to the presence of the minerals chlorite, actinolite, or epidote. Greenschist *facies* represents rocks that have experienced relatively low-grade regional metamorphism in the range of 300º to 500ºC (570º to 930ºF).

Greenstone. A general field term for any compact dark-green altered or metamorphosed basic *igneous* rock (like *basalt*) that owes its greenish color to minerals chlorite, actinolite, or epidote. Greenstone is a typical rock formed in metamorphic *greenshist facies*.

Headlands. A projection of the land into the sea, such as a peninsula or promontory.

Holocene. The name applied to the time span that corresponds with the post-glacial warming period in which we now live. The Holocene Epoch began about 11,000 years ago (at the end of the *Pleistocene* Epoch of the *Quaternary* Period), about the time that human population growth and distribution expanded worldwide.

Igneous. A rock or mineral that solidified from molten or partly molten material (referring to magma underground or lava on the surface). The word igneous also applies to the processes related to the formation of such rocks. Examples of igneous rocks include granite, *gabbro*, and *basalt*.

Intensity. A measure of ground shaking describing the local severity of an earthquake in terms of its effects on the Earth's surface and on humans and their structures. The Modified Mercalli Intensity (MMI) scale, which uses Roman numerals, is one way scientists measure intensity (see discussion in chapter 1).

Intrusive. *Igneous* rocks that forms from the process of emplacement of magma in pre-existing rock. Intrusive igneous rocks typically cool slowly compared to extrusive igneous rocks formed on the Earth's surface and therefore commonly have a coarse crystalline texture (like granite). The word intrusive applies to both the intrusion process and the rock so formed.

Jurassic. The second period of the *Mesozoic* Era (after *Triassic* Period and before *Cretaceous* Period) and spans the period of time between about 206 and 144 million years ago.

Landslide. A general term covering a wide variety of mass-movement landforms and processes involving the downslope transport of soil and rock under the influence of gravity. Usually the displaced material moves over a relatively confined zone or surface of shear. Landslides have a great range of morphologies, rates, patterns of movement, and scale. Their occurrence reflects bedrock and soil characteristics and material properties affecting resistance to shear. Landslides are usually preceded, accompanied, and followed by perceptible *creep* along the surface of sliding and (or) within the slide mass. *Slumps*, *debris flows*, rockfalls, avalanches, and mudflows are all forms of landslides.

Linear trough. A straight valley that may be bounded by linear fault scarps. A linear trough may be a *graben* or a *rift valley* and may be modified by erosion.

Linear drainage. A stream drainage that follows the trace of a fault. Stream alignment may be a result of *strike-slip fault* motion or the erosion of sheared and pulverized rock along a *fault zone*.

Linear ridge. A long hill or crest of land that stretches in a straight line. It may indicate the presence of a *fault* or a fold (such as an *anticline* or *syncline)*. If it is found along a *strike-slip fault* it may be a *shutter ridge* or a *pressure ridge*.

Linear scarp. A straight *escarpment* where there is a vertical component of offset along a *fault* (either *normal* or *reverse*). Linear scarps may also form when preferential erosion removes softer bedrock or soil along one side of a fault.

Mafic. A mnemonic term combining and “Ma” (for magnesium) and “Fe” (for ferric iron). The term is used to describe dark-colored igneous minerals rich in iron and magnesium, as well as the rocks that bear those minerals. See also ultramafic.

Magnitude (M). A numeric measure that represents the size or strength of an earthquake, as determined from seismographic observations (see discussion in chapter 1).

Mesozoic. The era of geologic time spanning about 248 to 65 million years ago. The Mesozoic Era follows the *Paleozoic* Era and precedes the Cenozoic Era. The *Mesozoic* Era is subdivided into the *Triassic*, *Jurassic*, and *Cretaceous* Periods. The term also applies to rocks that formed and accumulated in that time period.

Metamorphic. Pertaining to the process of metamorphism or to its results. Metamorphism is the mineralogical, chemical, and structural adjustment of solid rocks to physical and chemical conditions imposed at depth below the surface and below surficial zones where processes of sedimentation, compaction, and cementation take place. Examples of metamorphic rocks include slate, marble, quartzite, greenstone, gneiss, and schist.

Mid-oceanic ridges. Continuous submarine mountain ranges that extend for thousands of miles beneath portions of the North and South Atlantic Oceans, the South Pacific Ocean, and Indian Ocean. Mid-oceanic ridges are associated with spreading centers and are a source of new crustal material. (See also *spreading center*.)

Miocene. An epoch of the late *Tertiary* Period, after the Oligocene Epoch and before the *Pliocene* Epoch, representing the time span between about 23.8 and 5.3 million years ago.

Nonconformity. An *unconformity* between stratified rocks above (such as *sedimentary* rocks or lava flows) and unstratified *igneous* or *metamorphic* rocks below.

Normal fault. A *fault* in which the hanging wall appears to have moved downward relative to the footwall. The dip angle of the slip surface is between 45 and 90 degrees. Many normal faults in mountainous regions form from gravitational pull along mountainsides and may be associated with the headwall escarpment of slumps.

Oblique-slip faults. Faults that display significant components of both horizontal (*strike-slip*) and vertical (*dip-slip*) motion.

Offset drainage. A stream that displays offset by relatively recent movement along a *strike-slip fault*. A better term is *deflected drainage*.

Ophiolite. An assemblage of *mafic* and *ultramafic* igneous rocks ranging from *basalt* to *gabbro* and *peridotite*, including rocks derived from them by later *metamorphism* (such as *serpentinite*), and whose origin is associated with the upper mantle and the formation of oceanic crust at *spreading centers* in deep ocean basin settings.

Paleozoic. The era of geologic time spanning about 543 to 248 million years ago. The Paleozoic Era follows the Precambrian Era and precedes the *Mesozoic* Era. The term also applies to rocks that formed and accumulated in that time period.

Peridotite. A coarse-grained *intrusive igneous* rock composed chiefly of the mineral olivine, with or without other *mafic* minerals, such as amphiboles, pyroxenes, or micas, and contains little or no feldspar. Peridotite is believed to be a common rock in the upper mantle to lower oceanic crust. Peridotite is commonly altered to *serpentinite*.

Pillow basalt. A typically dark volcanic rock that is characterized by discontinuous pillow-shaped masses and is considered to be a product of lava flowing and chilling to form rock under water, such as on an underwater volcano. (See also *basalt*.)

Plate tectonics. The scientific theory that the Earth’s outer shell is composed of several large, thin, relatively strong “plates” that move relative to one another. Movements on the faults that define plate boundaries produce most earthquakes.

Pleistocene. The *Quaternary* Period is subdivided into the Pleistocene Epoch and the *Holocene* Epoch. The Pleistocene Epoch represents the time span of about 1.8 million to about 11,000 years ago. Many episodes of continental glaciation and intervening ice-free periods occurred within the Pleistocene Epoch. The Holocene Epoch began about 11,000 years ago, about the time that human population growth and distribution expanded worldwide.

Pliocene. An epoch of the late *Tertiary* Period following the *Miocene* Epoch and proceeding the *Quaternary* Period (or *Pleistocene* Epoch) and representing the time span from about 5.3 to 1.8 million years ago. The cycles of ice-age glaciations and intervening warming periods began in Pliocene time.

Plutonic rock. A rock formed at considerable depth by crystallization of magma and/or by chemical alteration. It is characterically medium- to coarse-grained with a granitic texture.

Porcellanite. A dense siliceous rock having the texture and general appearance of unglazed porcelain. It is associated with *sedimentary* rocks formed from deposits rich in planktonic skeletal material (marine ooze) that a accumulated in ocean basin or marine platform settings.

Porphyry. An *igneous* rock of any composition that contains conspicuous mineral crystals (called phenocrysts) in a fine-grained groundmass.

Pressure ridge. A pressure ridge is a topographic ridge produced by compressional forces along a *strike-slip fault* zone. Pressure ridges typically are located where there are bends along a fault or where faults intersect or *stepover*. Pressure ridges can be *shutter ridges* and can occur on one or both sides of a *fault* or within a *fault zone*.

Pull-apart basin. A surface depression will form along a fault where down warping of the surface occurs, such as from a developing fold or a fault-bounded *graben*. Closed depressions can form where extensional bends or *stepovers* occur along a *strike-slip fault* zone.

Quaternary Period. The period of time spanning about 1.8 million years ago to the present. The Quaternary Period is subdivide into two unequal epochs–the *Pleistocene* Epoch extends from about 1.8 million years ago to about 11,000 years ago, and the *Holocene* Epoch that extends from about 11,000 years ago to the present. The *Quaternary* Period encompassed many cycles of ice-age continental glaciations and intervening warming periods. The *Holocene* Epoch corresponds with the last warming period in which we now live.

Reverse fault. A *fault* in which the hanging wall has moved up relative to the footwall.

Rift valley. A valley that has formed along a tectonic rift. Rift valleys may be *grabens* or *pull-apart basins*, may be structurally complex, and are typically modified by erosion.

Riparian. Natural habitats associated with stream valleys and flood plains and having an abundance of phreatophytes (plants that send roots down to shallow water tables typical of floodplains).

Rockfall. The relatively free falling or precipitous movement of a newly detached segment of bedrock of any size from a cliff or very steep slope; it is most frequent in mountainous areas during spring when there is repeated freezing and thawing of water in cracks in rock. Movement may be straight down or in a series of leaps and bounds down the slope; it is not guided by an underlying slip surface (like a *slump*).

Roof pendant. A downward projection of rock into an *igneous* intrusion (also just called pendant). Pendants are remnants of the original bedrock that existed in the crust before igneous intrusion occurs. Pendants may range in size from large boulder-size blocks to mountain-size blocks.

Rupture zone. The area of the Earth through which fault movement occurred during an earthquake. For large earthquakes, the section of the fault that ruptured may be several hundred miles in length. Ruptures may or may not extend to the ground surface.

Sag pond. If a natural depression associated with a fault or associated with a *pull-apart basin* along a *fault system* can hold water, even temporarily, it is called a sag pond.

Salinian Complex. *Crystalline basement* rocks dominantly of *granitic* composition found west of the San Andreas Fault. The Salinian Complex includes intrusive igneous rocks of *Cretaceous* age that have intruded older metamorphic and igneous rocks. Salinian rocks are thought to have formed in the region that is now southern California and have migrated northward along *strike-slip fault systems* along the western continental margin, including along the modern San Andreas Fault and other faults that predate it.

Sedimentary. Materials consisting of sediments or formed by deposition. The word sedimentary applies to both the processes and the products of deposition. Examples of sedimentary rocks include shale, sandstone, *conglomerate*, limestone, and *chert*.

Seismic hazard. The potential for damaging effects caused by earthquakes. The level of hazard depends on the magnitude of likely quakes, the distance from the fault that could cause quakes, and the type of ground materials at a site.

Seismicity. The likelihood of an area being subject to *earthquakes*, or the phenomenon of earth movements.

Serpentinite. An *ultramafic* rock consisting almost wholly of serpentine-group minerals (such as antigorite and chrysotile) derived from the alteration of *peridotite*. Accessory chlorite, magnetite, and talc may be present.

Shutter ridges. A shutter ridge is a ridge formed by vertical, lateral, or oblique displacement on a *fault* that crosses an area having ridge and valley topography, with the displaced part of the ridge “shutting in” the valley. Shutter ridges typically are found in association with *offset drainages*.

Sidehill benches. A step-like surface on the side of a hill or mountain. Both recent fault activity or erosional differences of bedrock lithology across a fault may produce sidehill benches and associated *linear scarps*. Sidehill benches may also form from *slumping* that may or may not be associated with faulting.

Slickensides. A polished and striated rock surface produced by friction along a *fault*.

Slip. The relative displacement of formerly adjacent points on opposite sides of a *fault*, measured along the fault surface.

Slump. A type of *landslide* where the downward slipping mass of unconsolidated material or rock moves as a unit. A slump block usually displays backward rotation and on a more or less horizontal axis parallel to the slope or cliff from which it descends. Slumps typically form a fault-like escarpment and may occur at the head of a *landslide*.

Spreading center. A linear area where new crust forms where two crustal plates are moving apart, such as along a mid-oceanic ridge. Spreading centers are typically seismically active regions in ocean basins and may be regions of active or frequent volcanism.

Stepover. Closely spaced *strike-slip faults* within a greater *fault zone* over which the total displacement is distributed.

Strike. The direction taken by a structural surface, such as a layer of rock or a fault plane, as it intersects the horizontal.

Strike-slip fault. A generally vertical fault along which the two sides move horizontally past each other. If the block opposite an observer looking across the fault moves to the right, the slip style is termed “right lateral.” If the block moves to the left, the motion is termed “left lateral.” California’s San Andreas Fault is the most famous example of a right-lateral strike-slip fault.

Subduction zone. A boundary along which one plate of the Earth’s outer shell descends (subducts) at an angle beneath another. A subduction zone is usually marked by a deep trench on the sea floor. An example is the Cascadia Subduction Zone offshore of Washington, Oregon, and northern California. Most tsunamis are generated by subduction-zone-related earthquakes.

Syncline. A fold in rock strata, generally convex downward, whose core contains the stratigraphically younger rocks. (Opposite of *antincline*.)

Tafoni. A pocket-like or honeycomb-like weathering pattern that forms on barren outcrops, typically massive sandstone, and typically beneath overhanging surfaces.

Terrace. A relatively level bench or step-like surface breaking the continuity of a slope. Natural bench-like terrace features include elevated-marine terraces (along rising sea coasts), stream terraces (along incising streams), or structural terraces (such as along a *fault*).

Tertiary. The first period of the *Cenozoic* Era (after the *Cretaceous* Period of the *Mesozoic* Era). The Tertiary Period spans the time of about 65 to 1.8 million years ago. The Tertiary Period is subdivided into 5 epochs—Paleocene, Eocene, Oligocene, *Miocene*, and *Pliocene*). It is followed by the *Pleistocene* Epoch of the *Quaternary* Period.

Thrust fault. A fault with a dip angle of 45º or less over its extent on which the hanging wall appears to have moved upward relative to the footwall. Horizontal compression or rotational shear is responsible for displacement. (See also *reverse fault* and *oblique-slip fault*.)

Tonalite. Another name for quartz diorite. It is an *intrusive igneous* rock with an intermediate mix of light- and dark-colored minerals (diorite) with about 5 to 20 percent of the light-colored minerals being quartz.

Transform fault. A special variety of *strike-slip fault* along which the displacement suddenly stops or changes form. Many transform faults are associated with mid-oceanic ridges and plate boundaries that show pure strike-slip displacement, like the San Andreas Fault.

Tsunami. A sea wave of local or distant origin that results from large sea-floor displacements associated with powerful earthquakes, major submarine landslides, or exploding volcanic islands.

Turbidite. A sedimentary deposit, typically consisting of shale, sandstone, and sometimes *conglomerate*, that displays graded bedding and is believed to have been deposited by submarine turbidity currents associated with undersea landslides.

Ultramafic. A rock composed chiefly of *mafic* minerals (rich in iron and magnesium, and less than about 45 percent silica, such as olivine, augite, or hypersthene. Pyroxene and serpentinite are ultramafic rocks.

Unconformity. A gap or break in the geologic record, such as an interruption in the normal sequence of deposition of *sedimentary* rocks, or a break between eroded *igneous* and *metamorphic* rocks and younger, overlying sedimentary strata. (See also *angular unconformity* and *nonconformity*.)

Vegetation contrast. A general term used to describe changes in vegetation cover between adjacent areas that may reveal differences in soils and bedrock composition, such as across a fault boundary.

Where’s the San Andreas Fault?

A Guidebook to Tracing the Fault on Public Lands in the San Francisco Bay Region

By Philip W. Stoffer

1. Introduction

This volume is a general geology field guide to the San Andreas Fault in the San Francisco Bay region (fig. 1-1). Before going out in the field, it is recommended that you read the chapter about your target destination and make note of the specific features you wish to see. Examine directions and maps so you can focus on driving while making observations about the surrounding landscape. Depending on your destination, check on weather, tides, and road conditions. Geologic maps are available for all areas described in each field-trip chapter.

This first chapter provides a brief overview of the San Andreas Fault in context to regional earthquake history

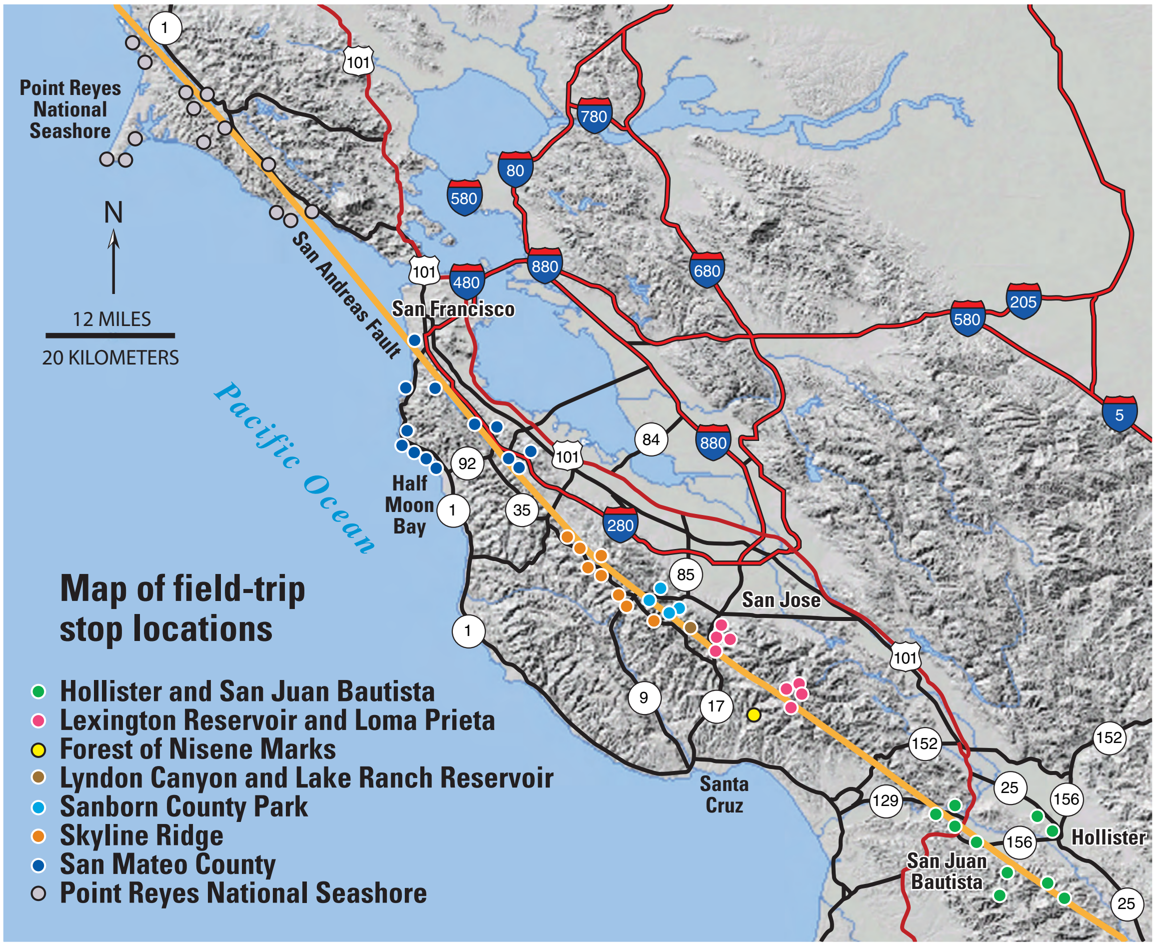


Figure 1-1. Map showing the field-trip destinations along the San Andreas Fault and vicinity. Small dots show the location of stops discussed in field-trip chapters. The orange line represents the San Andreas Fault section that ruptured in the earthquake of 1906.

and geology with emphasis of the section of the fault that ruptured in the Great San Francisco earthquake of 1906. This first section also contains earthquake information and discussions about making field observations of fault-related landforms, landslides and mass-wasting features, and the plant ecology in the San Francisco Bay region. The remainder of the volume is a collection of selected field-trip stops and recommended hikes on public lands in the Santa Cruz Mountains, along the San Mateo Coast, and at Point Reyes National Seashore. These trips focus on public-accessible locations along the San Andreas Fault and associated faults and on significant rock exposures and landforms. Note that more stops are provided in each of the sections than might be possible to visit in a day. This extra material is intended to provide optional choices to visit in a region with a wealth of natural resources. Selected references provide a more technical and exhaustive overview of the fault system and geology in the San Francisco Bay region.

Although this resource is intended as an introductory guide, some discussions contain more technical information necessary to maintain scientific accuracy. A limited glossary at the front of the guide is provided for frequently used terms. A review of a basic high-school or introductory college Earth science or geology textbook would be useful for individuals who have not taken or had an introductory geology course.

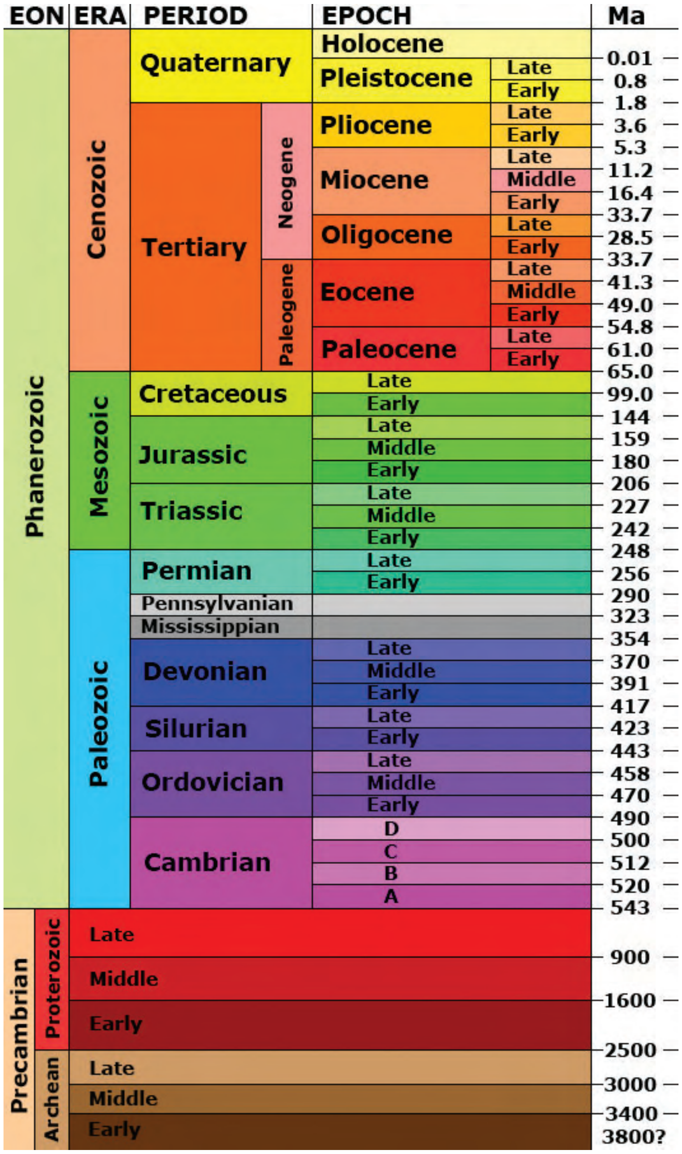
An important companion publication about earthquake awareness and safety that everyone living in the region should see is *Putting Down Roots In Earthquake Country—Your Handbook For The San Francisco Bay Region* (http://pubs.usgs.gov/gip/2005/15/). More information about the San Andreas Fault, earthquakes, and regional of geology of California can be found on the U.S. Geological Survey (USGS) website at http://www.usgs.gov/.

San Andreas Fault—An Overview

The catastrophe caused by the 1906 earthquake in the San Francisco Bay region started the study of earthquakes and California geology in earnest. Three days after the earthquake, Andrew C. Lawson, the chairman of the Geology Department at the University of California, Berkeley, organized (and was appointed head of by the Governor) a State Earthquake Investigation Commission. As a result, the "Lawson Report" (Lawson, 1908) was released. This massive volume contains detailed engineering studies of urban damage caused by the earthquake and fire and includes studies of surface rupture and ground failure along the San Andreas Fault throughout the region. The Lawson Report is still regarded as a significant scientific resource and is hailed as the first organized effort to study earthquake hazards and fault geology in the United States. In the century following the earthquake, several thousand technical reports and articles have been written about the San Andreas Fault system, and this body of knowledge was a fundamental part of the development of the theory of plate tectonics and the chronology of geologic events and processes that have shaped the landscape over time. Figure 1-2 is a time scale with standard names for geologic time intervals used in this report.

A Right-Lateral Strike-Slip Fault Motion

A major question raised by the 1906 earthquake investigations was why did the surface rupture along the San Andreas Fault show mostly horizontal offset? Although the surface rupture along the fault was highly variable, it was obvious that the west side of the fault had moved northward



EON	ERA	PERIOD		EPOCH		Ma
Phanerozoic	Cenozoic	Quaternary		Holocene		0.01
				Pleistocene	Late	0.8
					Early	1.8
		Tertiary	Neogene	Pliocene	Late	3.6
					Early	5.3
				Miocene	Late	11.2
					Middle	16.4
					Early	33.7
				Oligocene	Late	28.5
					Early	33.7
			Paleogene	Eocene	Late	41.3
					Middle	49.0
					Early	54.8
				Paleocene	Late	61.0
					Early	65.0
	Mesozoic	Cretaceous		Late		99.0
				Early		144
		Jurassic		Late		159
				Middle		180
				Early		206
		Triassic		Late		227
				Middle		242
				Early		248
	Paleozoic	Permian		Late		256
				Early		290
		Pennsylvanian				323
		Mississippian				354
		Devonian		Late		370
				Middle		391
				Early		417
		Silurian		Late		423
				Early		443
		Ordovician		Late		458
				Middle		470
				Early		490
		Cambrian		D		500
				C		512
				B		520
				A		543
Precambrian	Proterozoic	Late				900
		Middle				1600
		Early				2500
	Archean	Late				3000
		Middle				3400
		Early				3800?

Figure 1-2. Geologic time scale. Time subdivisions and geologic ages in millions of years (Ma) are after the Geological Society of America 1999 Geologic Time Scale [http://www.geosociety.org/science/timescale/timescl.pdf].

relative to the east side as much as 20 feet near Point Reyes. This “right-lateral offset” was not typical of previously studied earthquake surface ruptures and was contradictory to existing theories of processes responsible for the evolution of the landscape. Studies of the San Andreas Fault and California geology have since demonstrated that some massive blocks of rock have indeed moved laterally a great distance over geologic time. Landscape features, such as streams and geologically similar bedrock blocks (including distinct volcanic and plutonic rocks and unique sedimentary deposits of all ages), are all offset along the fault, with young rocks offset less than older rocks. The amount and rate of offset along the fault is not consistent from place to place, partly because at the surface the San Andreas Fault often consists of a complex system of parallel and interconnecting faults. Some sections of the fault are constantly creeping along, while other sections are locked during periods between episodic large earthquakes. In general, the western Pacific Plate is moving northward at about two inches per year relative to the North American Plate, and much of this motion is accommodated along the San Andreas Fault and is responsible for many large magnitude earthquakes (see figs. 1-3 and 1-4). However, the physical offset of the brittle crust near the Earth’s surface occurs along a number of known and unknown faults, often in an unpredictable fashion. In addition, movement along the San Andreas Fault is not purely right-lateral. There is a component attributed to compressional forces developed across the fault trace as the two plates grind against each other. This compression helped produce the coastal mountain ranges along the fault system throughout California. The ratio of compression to horizontal displacement typically ranges from 1:10 to 1:20 but varies considerably from one section or strand of the fault to another.

San Francisco Bay Area Faults and Earthquakes

The Earth’s crust in the San Francisco Bay region is broken by hundreds of known faults (and perhaps thousands of unmapped or undiscovered faults). However, only a small percentage of faults extend for distances measurable in miles, and of these, only a few are associated with historical earthquake activity (fig. 1-5). The most active fault in the region is the San Andreas Fault; however, all of the large faults in the San Francisco Bay region that display recent earthquake activity or that display Quaternary offset are part of the greater San Andreas Fault system. Many Bay Area faults are described in detail in the *Quaternary faults and fold database of the United States* website [http://earthquakes.usgs.gov/qfaults/]. Geologic maps and subsurface fault information in the Bay Area is available from the *San Francisco Bay region geology* website [http://sfgeo.wr.usgs.gov].

Thousands of small, almost imperceptible earthquakes occur in the San Francisco Bay region each year, only a handful of which make local news. However, in the period from 1800 to the present, the San Francisco Bay region has been shaken by 21 earthquakes of magnitude (M) 6.0 or greater. Of these, six were in the range of magnitude 6.5 to 7.0. An earthquake of damaging magnitude could happen at any time on any of a number of faults. It is the faults located in urbanized areas that most concern geologists (and should concern the public), particularly the Hayward, Calaveras, and Rogers Creek faults, but there are many more known faults and potentially others that have not yet been discovered or technically evaluated. However, the San Andreas Fault has historically produced the largest earthquakes—the Loma Prieta earthquake of 1989 was probably a magnitude 6.9, and the Great San Francisco earth-

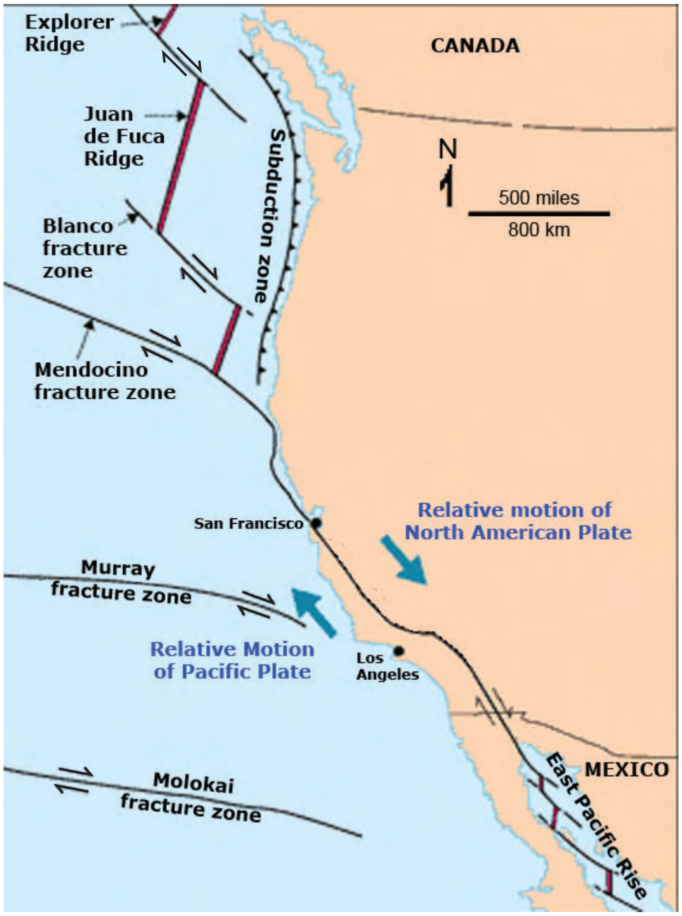


Figure 1-3. Map of the San Andreas Fault in relation to the greater plate-tectonic setting of western North America and the northeastern Pacific Ocean basin. The San Andreas Fault represents a great transform-fault boundary between the North American Plate and the Pacific Plate. The San Andreas Fault system connects between spreading centers in the East Pacific Rise (to the south) and the Juan de Fuca Ridge and Mendicino fracture zone system (to the north). The San Andreas Fault system has gradually evolved since middle Tertiary time (beginning about 28 million years ago; see fig. 1-7). The right-lateral offset that has occurred on the fault system since that time is about 282 miles (470 km); however, the fault system consists of many strands that have experienced different amounts of offset (see fig. 1-4). Image modified from U.S. Geological Survey, 2003, *This Dynamic Earth* (http://pubs.usgs.gov/gip/dynamic/dynamic.html).

quake of 1906 was in the range of magnitude 7.9 (see Table 1). Another earthquake in the magnitude 7.0 range occurred along the Peninsula section of the San Andreas Fault in 1838, and others preceded it, but very little is known about these events. (Source: *California earthquake history 1769-present* [http://pasadena.wr.usgs.gov/info/cahist_eqs.html].)

Comparison of Earthquake Magnitude and Intensity

The effects of earthquakes are reported in two ways—magnitude (the amount of energy released by an earthquake) and intensity (a measure of the shaking produced by an earthquake). Magnitude (M) is determined from the study of seismograms, which are a record of Earth motion recorded by seismographs. The original earthquake magnitude scale was defined by Charles Richter in 1935. The Richter scale or "local" scale (ML) assigned earthquake magnitudes a number on a logarithmic scale of increasing intensity. However, modern magnitude scales are calculated based on the area of fault rupture times the amount of slip—this is called seismic moment. The moment magnitude (MW) provides a more reliable estimate of the size of an earthquake. Equations to calculate seismic moment (and moment magnitude) also include corrections that factor in the physical properties of the rocks sheared by an earthquake. The difference between ML and MW are negligible at lower magnitudes. In addition, the measure of earthquake magnitudes relies or the gathering of information

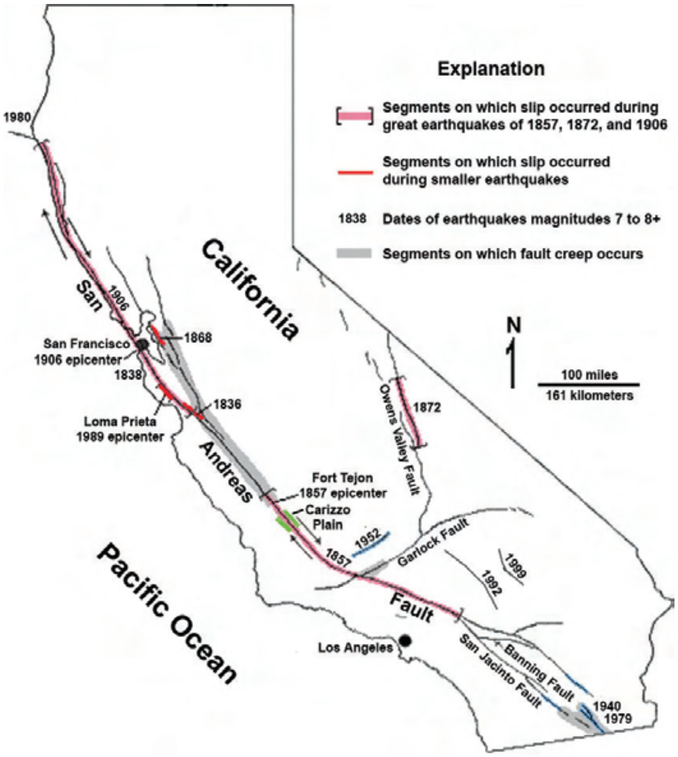


Figure 1-4. The San Andreas Fault system has a historical record of moderate to great earthquakes. The surficial expressions of the two greatest historical earthquakes on the San Andreas Fault are fairly well documented. The San Francisco earthquake of 1906 was similar in magnitude to the Fort Tejon earthquake of 1857. Both are traditionally reported to have been in the magnitude 7.8 to 8.3 range. The 1906 quake was documented by many witnesses including Gilbert (1908) and Lawson (1908). In contrast, the 1857 earthquake occurred in a very sparely populated region, but arid conditions have helped to preserve geomorphic features associated with the fault and the earthquake (including in what is now Carrizo Plain National Monument). A land survey conducted in the Carrizo Plain region shortly before the 1857 earthquake has provided a baseline for modern investigations in that area. (Map source modified from Schulz and Wallace, 1997.)

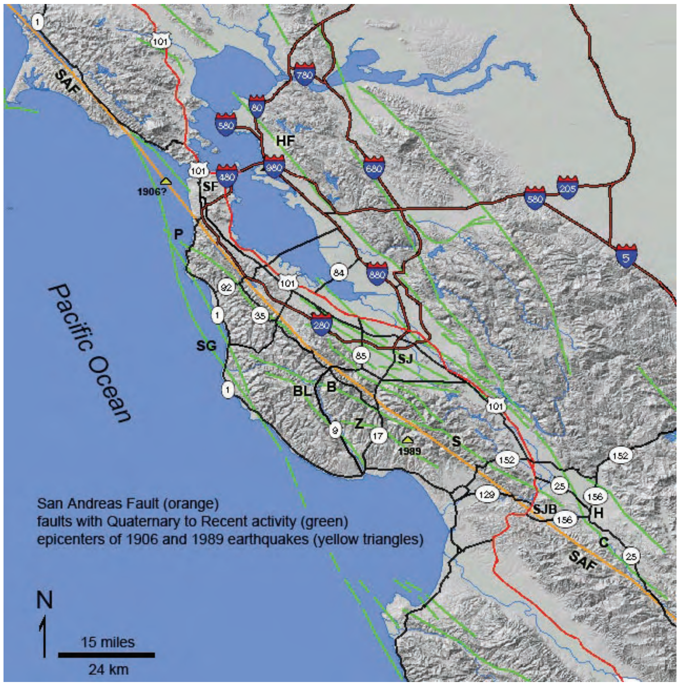


Figure 1-5. Map showing the trace of the San Andreas Fault (shown in orange) through the San Francisco Bay region. Additional faults that have had Quaternary-age and historical earthquake activity or movement are shown in green. The location of the epicenter of the 1989 Loma Prieta earthquake and the possible offshore epicenter of the 1906 earthquake are shown as yellow triangles. The 1906 earthquake produced surface rupture from San Juan Bautista northward to where it extends offshore at Cape Arena. The 1906 earthquake probably also ruptured northward toward the Mendicino Triple Junction offshore from the California-Oregon border. In contrast, the surficial effects of the Loma Prieta earthquake were mostly limited to the region between California Highways 17 and 152. The San Andreas Fault south of San Juan Bautista is part of the "creeping section" of the fault. Letter labels of selected faults include the San Andreas Fault (SAF), Calaveras Fault (C), Hayward Fault (HF), San Gregorio Fault System (SG), Zayente Fault (Z), Butano Fault (B), Ben Lomond Fault (BL), Sargent Fault (S), and Pilarcitos Fault (P). Cities include San Francisco (SF), San Jose (SJ), Hollister (H), and San Juan Bautista (SJB). (Source: http://earthquake.usgs.gov/qfaults/.)

Table 1. Comparison of the 1906 San Francisco and 1989 Loma Prieta earthquakes.

Great San Francisco Earthquake (1906)	**Loma Prieta Earthquake (1989)**
Time: 5:12 AM—April 18,1906	**Time**: 4:15 PM—October 17, 1989
Duration: 45 to 60 seconds	**Duration:** 10 to 15 seconds
Magnitude (M): 7.9, although historical estimates were as high as 8.3. Modern estimates range from 7.7 to 7.9.	**Magnitude (M):** 6.9. The 1989 Loma Prieta earthquake was only about 1/32 as intense as the 1906 earthquake.
Highest Modified Mercalli Intensities: Shaking intensities of VIII (moderate damage) to IX (heavy damage) extending as much as 60 miles (97 km) inland along a broad band paralleling the fault trace—depending of competence of subsurface materials in soils or fill versus bedrock. Heavy shaking and damage occurred throughout the San Francisco Bay region with the greatest amount of damage affecting the urban areas of San Francisco, Santa Rosa, Hayward, San Jose, and San Juan Bautista.	**Highest Modified Mercalli Intensities:** Intensities X (extreme damage) to IX (heavy damage) was limited to the vicinity of the San Andreas Fault trace in the southern Santa Cruz Mountains from Highway 17 to near Aromas in Santa Cruz County. Most of the San Francisco Bay Area only experienced V (strongly felt) to VII (light damage). VIII (moderate damage) occurred throughout much of eastern Santa Cruz County and in areas around San Francisco Bay underlain by poorly consolidated sediments and artificial fill. Some of the heaviest damage occurred in San Francisco's Marina District and China Basin (these same areas were mostly built on fill made up of debris from the 1906 earthquake and fire).
Length of fault rupture: about 300 miles (480 km) from the San Juan Bautista area northward to the Mendicino Triple Junction (offshore).	**Length of fault rupture:** about 25 miles (40 km) in the southern Santa Cruz Mountains east of Highway 17.
Epicenter: Current scientific thought is that the epicenter was west of San Francisco in the Pacific Ocean (west of Thornton State Beach). Earlier reports suggested that the epicenter was closer to Point Reyes where the greatest offset was reported.	**Epicenter:** Located in the Forest of Nisene Marks State Park between Loma Prieta Peak and Santa Cruz (37.040 N, 121.877 W). The earthquake hypocenter occurred at a depth of 11 miles (18 km), located approximately 4 miles (6 km) west of the surface trace of the San Andreas Fault (the fault plane dips at an angle of about 75 degrees to the west).
Fault rupture characteristics: As much as 20 feet of right-lateral offset was reported near Point Reyes (Lawson, 1908), with a greater amount projected at depth. More recent projections include as much as 24 feet at depth at Point Reyes and as much as 20 feet near Point Reyes. In the San Francisco Peninsula region, offset was in the range of 9 to 12 feet and diminished southward. Offset of 3 to 5 feet (1-2 m) was reported in the San Juan Bautista area. No surface rupture was reported farther south, but strong earthquake shaking was reported in this largely uninhabited region.	**Fault rupture characteristics:** Estimates of 6.2 feet of horizontal right-lateral displacement with 4.2 feet of vertical (reverse) displacement, with uplift on the west side relative to the east side of the fault. Debate still continues among scientists on whether the 1989 Loma Prieta earthquake actually occurred within the San Andreas Fault Zone.
People killed or injured: 700 deaths were initially reported, but revised estimates are closer to 3,000 killed by the earthquake and subsequent fire in San Francisco. Many thousands were injured.	**People killed or injured:** 63 deaths were reported, and nearly 400 people were severely injured. Total reported injuries were about 4,000.

Table 1. Continued.

Bay Area population in 1906: About 400,000.	**Bay Area population in 1989:** About 6,000,000.
Number of people left homeless: About 250,000.	**Number of people left homeless:** About 3,000.
Buildings damaged: About 28,000 building were destroyed (mostly by extensive fires after the earthquake).	**Buildings damaged:** About 12,000 homes and 2,600 businesses were damaged or destroyed. Images of damage are available at: http://pubs.usgs.gov/dds/dds-29 .
Cost: Estimated to be about 400 million in 1906 dollars	**Cost:** Estimated to be about 6 billion in 1989 dollars
Source: The Great San Francisco earthquake: U.S. Geological Survey, Earthquake Hazards [http://quake.wr.usgs.gov/info/1906/].	**Sources:** McNutt and Sydnor, 1990; Wells, 2004; and the Berkeley Seismological Laboratory [http://www.seismo.berkeley.edu/seismo/faq/1989_0.html].

from seismic sensors—many earthquakes happen in remote regions or occurred before seismic networks were established. Modern earthquakes are simply reported as magnitude (M). The M scale is a logarithmic measure of seismic amplitude, with each whole number representing a 10-fold increase in seismic amplitude, and about 31.6 times the amount of energy released. For example, a strong earthquake of magnitude 6.4 would have the energy released 31.6 times greater than a moderate earthquake of magnitude 5.4. A two-unit increase (from magnitude 5.4 to 7.4) would release 1,000 times as much energy (31.6 x 31.6). Earthquakes below magnitude 2.5 are typically not felt by humans. Great earthquakes are in the range of magnitude 8 or more.

Intensity is a measure of the local severity of an earthquake based on surface ground shaking and is determined from the effects on people, buildings, infrastructure, and other factors related to the physical setting (for instance, whether a structure is built on unconsolidated bay mud versus solid bedrock). The Modified Mercalli Intensity Scale is used to report shaking intensity (see table 2).

There are other methods of measure of earthquake magnitude and intensity used by seismologists. Many factors come into play, such as the number and proximity of seismic stations to an earthquake epicenter and the direction of seismic motion. For more information on magnitude and intensity see http://earthquake.usgs.gov/.

Geologic Features of the San Andreas Fault

Geologic mapping of the State of California has revealed that great blocks of the Earth's crust have split away from their place of origin and have been carried northward along the San Andreas Fault system. However, much of this material had already been displaced long distances from its places of origin by plate-tectonic motion long before the modern San Andreas Fault had formed. Figure 1-6 shows a selected list of prominent, well-known or heavily investigated offset geologic features that support evidence about timing, rate of development, and cumulative amount of offset along the San Andreas Fault and associated faults throughout California. Rocks discussed in this section formed before and concurrent with the ongoing development of the San Andreas Fault. However, the fault system is far more complex, and the wealth of observable features in the field is much more diverse than presented here. For more information about fault-bounded blocks (also called "terranes") in the Santa Cruz Mountains, see Wells (2000) and Wentworth and others (1998).

Rocks West of the Fault

Mesozoic granitic basement rocks lie west of the San Andreas Fault from southern California northward to the San Francisco Bay region. These rocks occur as great crustal blocks that were carried northward along the western continental margin by plate-tectonic motion both before and during the development of the San Andreas Fault system. These granitic rocks, called Sur Series and the Salinian Complex, are exposed in the Gavilan Range, the Monterey Peninsula, Ben Lomond Mountain, Montara Mountain, and Point Reyes. These granites are overlain by marine sedimentary rocks of Tertiary age (ranging from about 55 million years in age, possibly older, to sedimentary deposits currently forming in offshore basins). Thick sequences of sedimentary rocks ranging from Eocene to Pliocene age were deposited in marine platform and basinal settings and represent environments ranging from deep abyssal fan to shelf and nearshore environments. These sedimentary deposits, along with some volcanic rocks, accumulated prior to, and concurrent with, the development of the San Andreas Fault and other regional faults of the

Table 2. Comparison of earthquake magnitude (energy released) and intensity (shaking and damage).

Magnitude (M)	Modified Mercalli Intensity (MMI)	
1.0- 1.9 (A magnitude 1 is roughly equivalent to a quarry blast and can be generated by non-earthquake related events, such as a rock fall.)	**I**	Earthquakes of this intensity are generally not felt.
2.0-2.9	**II**	Felt by only a few people at rest, especially on the upper floors of buildings.
3.0-3.9	**III**	Felt noticeably by people indoors or on upper floors of buildings but may not be recognized as an earthquake (similar to shaking by a passing truck, typically very short in duration).
4.0-4.9	**IV-V**	Felt noticeably by people both indoors and outdoors. Will wake some sleeping people. Walls will make cracking noises, and dishes, doors, and windows will rattle or move. Motor vehicles will rock noticeably. May cause unstable objects to fall or overturn; pendulum clocks may stop.
5.0-5.9 (A magnitude 5 earthquake is roughly equivalent to the force of a 10 kiloton nuclear blast, like that at Hiroshima, Japan.)	**VI-VII**	This intensity is felt by practically everyone. Damage is negligible in well-constructed buildings. Plaster may crack and fall; some chimneys may be broken.
6.0-6.9	**VII -IX**	Damage negligible in well-designed buildings. Slight to great damage to buildings and infrastructure of poor design.
7.0-7.9	**VIII**	Well-designed buildings may experience some damage. Building and bridges may shift off their foundations or partially collapse.
8.0-8.9	**X**	Wooden buildings may be destroyed. Few masonry structures remain standing. Bridges destroyed; rail lines are bent.
9.0 and higher	**XII**	Nearly every manmade structure is destroyed or heavily damaged. The ground is distorted. Objects are thrown into the air.

western Coast Ranges. These are in turn overlain by poorly consolidated sediments of Quaternary age (less than 2 million years old) that accumulated in shallow shelf, shelf, marginal marine, river, and inland-bay environments that developed and changed as the regional fault system evolved and as tectonic forces raised portions of the seabed west of the fault above sea level. Coastal marine terraces were cut by the rise and fall of sea level as continental glaciers formed and melted during the Quaternary ice ages. Studies of marine terraces have shown that different portions of the modern coastline are simultaneously rising or sinking and that these tectonic changes are associated with the regional fault system.

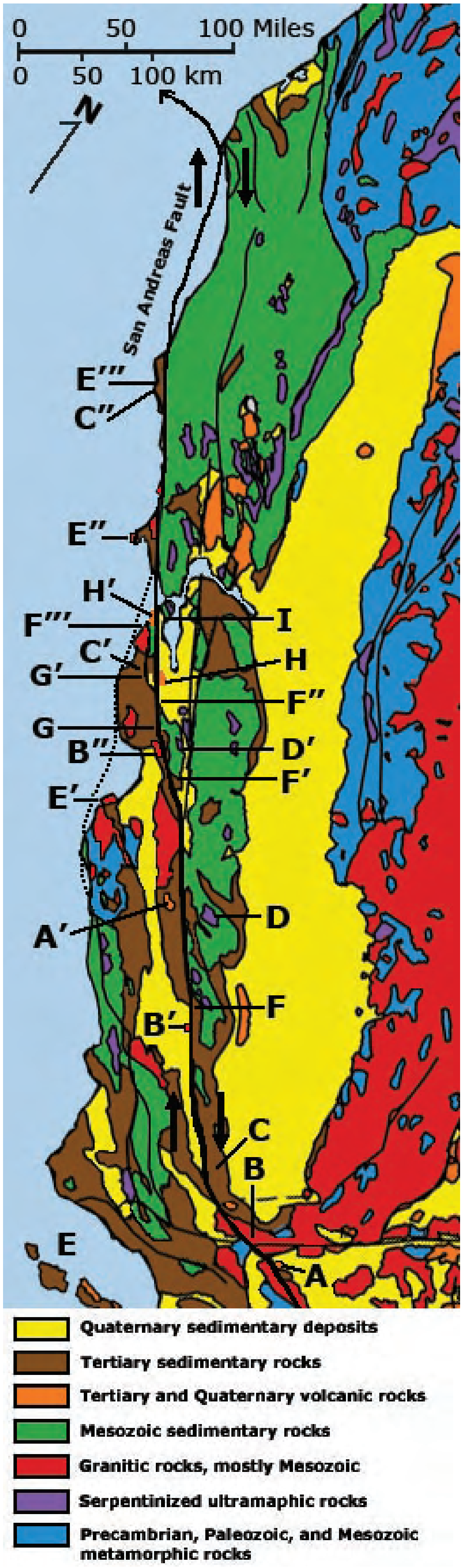
Rocks East of the Fault

East of the San Andreas Fault, rocks that predate the fault system include those of the Coast Range Ophiolite (consisting mostly of serpentinized ultramafic rocks and greenstone derived from the mantle and ocean crust) and Franciscan Complex (ribbon chert, limestone, greenstone, pillow basalt, mudrocks and sandstone formed in an ocean basin setting). These are juxtaposed or overlain by sedimentary rocks of the Great Valley Sequence (mostly sandstone, shale, and conglomerate that accumulated on the continental shelf or deep-water shelf-margin basin settings) that were deposited concurrently with material being thrust downward into a subduction zone in the region along what is now coastal California. When subduction ended after the Mid-Pacific Ridge was subducted, a series of volcanoes formed along a northward propagating rift, the incipient San Andreas Fault system (fig. 1-7). Through this period, the dominantly marine conditions of the Mesozoic Era gave way to estuaries, river deltas, and other terrestrial environments. Since late Tertiary time, coastal California must have appeared somewhat as it does today—a mix of low mountains (or islands), hills, lowland valleys, and bays, but with few similarities to the modern configuration of the coastal landscape (Barstow, 1991). For instance, a great bay extended northward from the Los Angeles region into the southern San Joaquin Valley until as recently as 4 million years ago. Since then the Coast Ranges have experienced both significant uplift and "unroofing" by erosion. In addition, tectonic forces associated with the fault systems have created crustal downwarps and fault-bounded pull-apart basins that concurrently filled with sediments derived from the surrounding uplands. These sediments were deposited on alluvial fans, along streams, and in shallow lakes and bays; processes that are ongoing throughout the region.

Interpreted History of Fault Motion

The northward transport of rocks was occurring before the San Andreas Fault formed, as recorded by some of the oldest rocks in the San Francisco Bay region—examples include ribbon cherts and limestones of the Franciscan Formation that must have originally accumulated in clear, mid-ocean equatorial waters during Jurassic time. The Cretaceous-age Calera Limestone is thought to have formed on seamounts in warm equatorial waters and were transported northward before being accreted onto the continental margin. Today, they are exposed throughout the Santa Cruz Mountains and near Point Reyes. These rocks were moved north, in part, by coastal fault systems including some that predate the San Andreas Fault. During Cretaceous to mid-Tertiary time much of this motion was associated with northeastward movement of the Farallon and Pacific Plates and their subduction beneath the North American continental margin (see fig. 1-7). In mid-Tertiary time subduction was replaced with right-lateral transform faulting that resulted in the propagation of the San Andreas Fault northward from the Los Angeles region starting about 28 million years ago. The leading edge of the fault system propagated through the San Francisco Bay region beginning about 12 million years ago, but the modern trace of the San Andreas Fault didn't develop until much more recently, probably in the past 5 to 7 million years. Meanwhile, other faults in the San Francisco Bay region have been and currently are more active in terms of rates of relative offset motion over time. Higher rates of fault motion are estimated for parts of the East Bay fault system (including the Calaveras and Hayward Faults), and in the past higher rates of motion may have occurred along the San Gregorio Fault system that runs along the coast and offshore (Irwin and others, 1990; Wentworth and others, 1998, Jachens and others, 1998, and Brown, 1990). Roughly 185 miles (300 km) of offset determined in the mid-section of the San Andreas Fault (based on A-A' and B-B' on fig. 1-6). Along the San Benito River Valley south of Hollister, the San Andreas Fault system diverges into two active earthquake faults, the Calaveras Fault to the east, and the San Andreas Fault to the west. Near Anderson Reservoir near Morgan Hill, the Calaveras Fault bifurcates into the Hayward Fault and Northern Calaveras Fault. At the surface these faults are complex, but seismic data suggests narrow fault zones exist at depth. Current estimates are that about 110 miles (175 km) of offset in the San Francisco Bay Area has occurred along the East Bay fault system, whereas the 82 miles (127 km) of offset occurred along the San Andreas Fault and other faults in the Santa Cruz Mountains on the San Francisco Peninsula. Of this, about 14 miles (22 km) has been absorbed on the modern San Andreas after about 65 miles (100 to 105 km) of offset occurred on the Pilarcitos/Montara Fault (Jachens and others, 1998). Another estimate suggests that as much as 93 miles (150 km) of offset has occurred along the San Andreas Fault in the southern Santa Cruz Mountains since Miocene time, of which about 17 miles (27 km) has occurred in the past 3 million years (McLaughlin and others, 2001).

Estimations of slip rates along the San Andreas Fault system vary from one location to the next and from one period of time to another. The separation of equivalent rocks in Baja California and along the west coast of Mexico demonstrate that the relative motion between the North American Plate and the Pacific Plate is in the range of about 2 inches (5 cm) per year for post-Pliocene time. Along the northern section of the San Andreas Fault system, the belt of late Tertiary and Quaternary faulting is as much as 75 miles (120 km) wide (extending from the eastern side of the Diablo Range to offshore) (Brown, 1990). Collectively in the San Francisco Bay region this would include the San Gregorio, San Andreas, Hayward, Calaveras, possibly a range-front fault system on the east side of the Diablo Range, and additional faults to the north. All of these faults display Quaternary offset and are considered seismically active. As a result, the nearly 2 inches (5 cm) of average annual offset per year that have been determined to take place across the North American Plate and Pacific Plate boundary is distributed between all of these faults. Slip-rate estimates on the San Francisco Peninsula section of the San Andreas



◄ **Figure 1-6.** Selected geologic ties across the San Andreas Fault system that help define the age and the rate and amount of offset along the regional fault system.

A, Early Miocene-age volcanic rocks (about 23 million years old): A, Neenach Volcanic Area; A‘, Pinnacles Volcanic Area; A-A’ offset distance about 195 miles (315 km) (Irwin, 1990).

B, Cretaceous-age plutonic rocks (about 80 to 100 million years old): B, gabbro at Eagle Rest Peak; B’, Gold Hill gabbro in the Parkfield area; B’’, Logan gabbro quarry; B to B’’ offset distance about 198 miles (320 km) (Irwin, 1990).

C, Eocene-age oil-bearing sedimentary rocks: C, Butano and Point of Rocks formations in the San Joaquin Basin; C’, Butano Formation in the La Honda Basin in the Santa Cruz Mountains; C’’, Eocene sedimentary rocks in the Gualala block; C to C’ offset distance about 198 miles (320 km); C’ to C’’ offset distance about 93 miles (150 km); total C-C’’ offset about 292 miles (470 km) (Wentworth and others, 1998).

D, Miocene-age mercury-bearing deposits in silica-carbonate rocks (18 to 10 million years old): D, Clear Creek and New Idria Mining District; D’, New Almaden Mining District; D to D’ offset distance about 165 miles (265 km).

E, Paleocene-age gravels bearing mafic clasts: E, Ventura River; E’, Point Lobos; E’’, Point Reyes; E’’’, Gualala block, Anchor Bay Formation (much of this offset is along the Sur-Nacimiento-Hosgri-San Gregorio Fault system), E to E’’’ offset distance about 364 miles (585 km).

F, Permanente Terrane (limestone and volcanic rocks of Cretaceous age): F, Parkfield; San Francisco Bay Area occurrences include the Calera Limestone in the Santa Cruz Mountains region: F’, Morgan Hill area (El Toro Peak); F’’, Stevens Creek quarry; F’’’, Rockaway Beach quarry; F to F’’’ offset distance about 217 miles (350 km). Some of this offset (between F’’ and F’’’) is along the Pilarcitos Fault, an older and possibly inactive segment of San Andreas Fault on the San Francisco Peninsula region (McLaughlin and others, 2001).

G, Gravels the Corte Madera facies of the Santa Clara Formation of Plio-Pleistocene age (3 to 1 million old) derived from the Loma Prieta and Mount Umunhum summit areas: G, Santa Clara Formation along Lexington Reservoir; G’, Corte Madera facies in the Los Trancos and Monte Bello preserves area; G to G’ offset is about 14 miles (23 km) (Brown, 1990).

H, Marine deposits of late Pliocene age show that a small coastal embayment that in the Stanford Hills area existed 2 to 3 million years ago; H, Stanford Hills deposits; H’, equivalent Pliocene-age marine deposits west of the fault; H to H’ offset is about 22 to 24 miles (35 to 40 km) (Brown, 1990).

I, Offset Merced Formation on the San Francisco Peninsula displays a minimum offset of 7 miles (11 km) for material 0.4 to 2.0 million years old (Brown, 1990).

(The base map of this image is modified after a generalized geologic map of California produced by the California Geological Survey.)

Fault are in the range of about an inch (1.6 to 1.7 cm) per year (based on fig. 1-6, sites G to G', and I). A rate for the southern Santa Cruz Mountains is between 1 and 3 cm per year (based on sites H to H'). As a result, the potential for damaging earthquakes is distributed across the regional fault system.

Types of Faults

A **fault** is a fracture between blocks of the Earth's crust across which movement has occurred (see fig. 1-8). Important fault terms include:

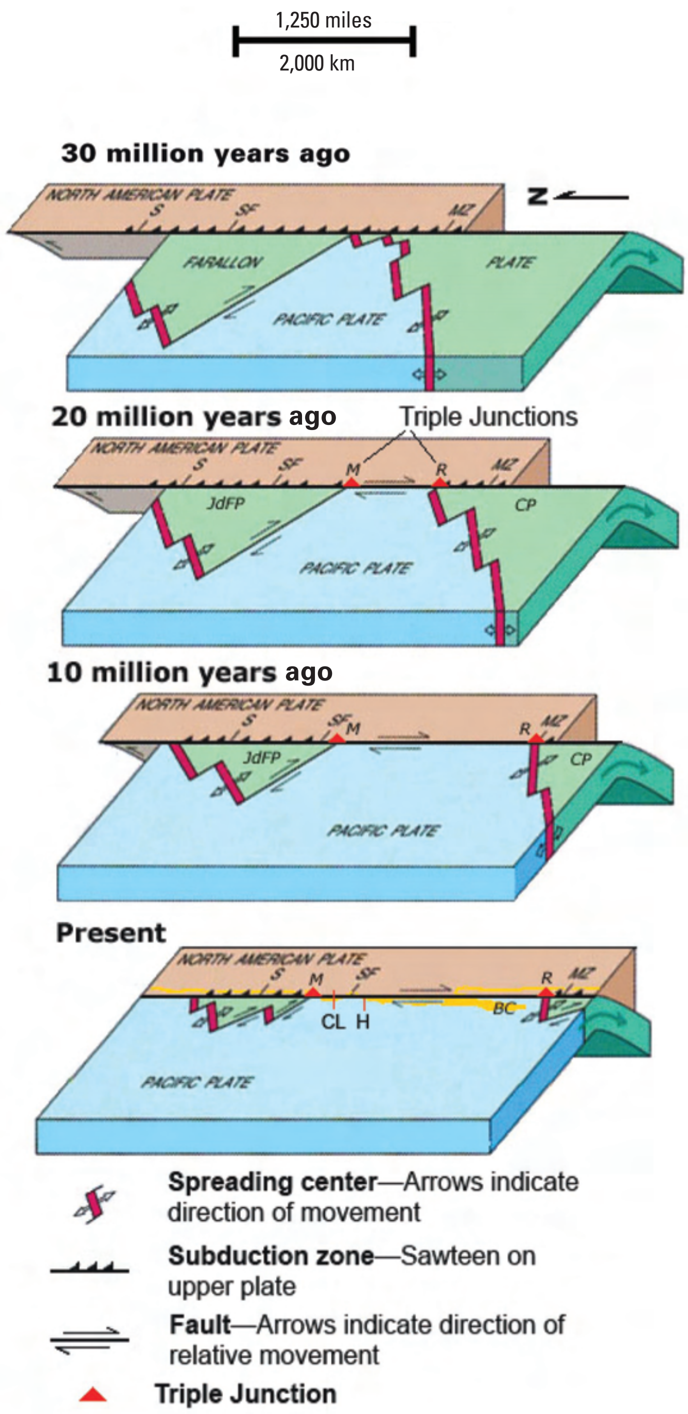
Strike-slip faults—Vertical (or nearly vertical) fractures where the blocks have mostly moved horizontally. If the block opposite an observer looking across the fault moves to the right, the slip style is termed "right lateral." If the block moves to the left, the motion is termed "left lateral."

Dip-slip faults—Inclined fractures where the blocks have mostly shifted vertically. If the rock mass above an inclined fault moves down, the fault is termed *normal*, whereas if the rock above the fault moves up, the fault is termed *reverse*. A reverse fault in which the fault plane is inclined at an angle equal to or less than 45° is called a *thrust fault*.

Oblique-slip faults—Faults that display significant components of both horizontal (strike-slip) and vertical (dip-slip) motion.

Fault-Related Terminology

Fault line—The trace of a fault plane on the ground surface or other surface, such as on a sea cliff, road cut, or in a mine shaft or tunnel. A fault line is the same as fault trace.



◄**Figure 1-7.** Evolution of the San Andreas Fault. This series of block diagrams shows how the subduction zone along the west coast of North America transformed into the San Andreas Fault from 30 million years ago to the present. Starting at 30 million years ago, the westward-moving North American Plate began to override the spreading ridge between the Farallon Plate and the Pacific Plate. This action divided the Farallon Plate into two smaller plates, the northern Juan de Fuca Plate (JdFP) and the southern Cocos Plate (CP). By 20 million years ago, two triple junctions began to migrate north and south along the western margin of the West Coast. (Triple junctions are intersections between three tectonic plates; shown as red triangles in the diagrams.) The change in plate configuration as the North American Plate began to encounter the Pacific Plate resulted in the formation of the San Andreas Fault. The northern Mendicino Triple Junction (M) migrated through the San Francisco Bay region roughly 12 to 5 million years ago and is presently located off the coast of northern California, roughly midway between San Francisco (SF) and Seattle (S). The Mendicino Triple Junction represents the intersection of the North American, Pacific, and Juan de Fuca Plates. The southern Rivera Triple Junction (R) is presently located in the Pacific Ocean between Baja California (BC) and Manzanillo, Mexico (MZ). Evidence of the migration of the Mendicino Triple Junction northward through the San Francisco Bay region is preserved as a series of volcanic centers that grow progressively younger toward the north. Volcanic rocks in the Hollister region are roughly 12 million years old whereas the volcanic rocks in the Sonoma-Clear Lake region north of San Francisco Bay range from only few million to as little as 10,000 years old. Both of these volcanic areas and older volcanic rocks in the region are offset by the modern regional fault system. (Image modified after original illustration by Irwin, 1990.)

Faults lines can often be difficult to resolve from general surface observation due to cover by younger sediments, vegetation, and human-induced landscape modifications.

Fault zone—A fault or set of related faults that is expressed as a zone of numerous small fractures or of "breccia" or "fault gouge." A fault zone may be hundreds of feet wide and may locally have a complex structure.

Fault system—A collection of parallel and (or) interconnected faults that display a related pattern of relative offset and activity across an entire region (for example, the San Andreas Fault system).

Earthquake fault—An active fault that has a history of producing earthquakes or is considered to have a potential of producing damaging earthquakes on the basis of observable evidence. Not all faults are active or are considered earthquake faults.

Geomorphic Features Observable Along the San Andreas Fault

The most conspicuous landscape features that reveal the location of the San Andreas Fault are structures that display evidence of right-lateral offset. Other characteristics include juxtaposed bedrock types, linear landscape features, springs, stream drainage patterns, and natural catchment basins with ponds. Vertical uplift along the fault (on one or both sides), or bifurcating or echelon fault patterns, folding, and the varying width and erosion along a active and past-active fault zone can create challenges in finding and following a fault trace. Stream patterns are typically revealing but must be verified by other lines of evidence. The fault trace is often obscured by topography (such as where a fault crosses hill slopes and stream divides), ground cover, landslides, soil and alluvium, colluvium, or surface disruption from human activity (fig. 1-9). The San Andreas Fault provides many of the key landscape features that form as fault motion impacts an eroding or changing landscape surface over time:

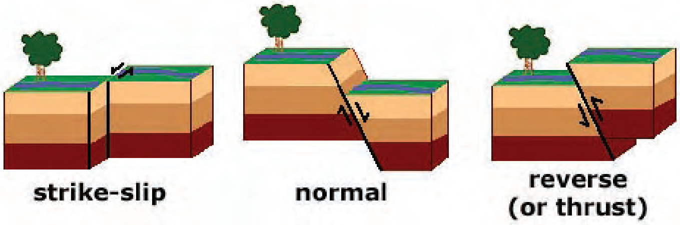


Figure 1-8. The strike-slip fault shown here displays right-lateral offset. Dip-slip faults include normal and reverse (or thrust) faults. Although strike-slip motion dominates, all three types of faulting and combinations of strike-slip and dip-slip can be observed along the San Andreas Fault and other faults in the San Francisco Bay region.

Offset manmade features—Offset cracks in roads, pipelines, fences, tree rows, buildings, and other damaged infrastructure may reveal the location of faults. The Bay Area has many famous examples of offset features, including examples along the San Andreas and Calaveras Faults in the Hollister region (illustrated in this guidebook) and the historic City Hall in Hayward (on the creeping Hayward Fault). Restored examples of offset fences can be seen at Los Trancos Open Space Preserve and along the Earthquake Trail near the Bear Valley Visitor Center at Point Reyes National Seashore.

Bedrock contrasts and evidence of faulting—Changes in lithology (rock types) are not always fault related, but major lithologic changes can be observed across faults throughout the San Francisco Bay region. These contrasts in bedrock may reflect both ancient and more recent fault activity. Bedrock contrasts are typically reflected by associated changes in weathering and erosion patterns (geomorphology) and differences in soil and vegetation characteristics. More direct evidence of faulting includes slickensides (a polished and striated rock surface produced by friction along a fault), and pulverized and fractured rock (or clay where weathering has occurred). It is important to note that surficial processes associated with slumping and landslides often produce features that can be easily confused with faulting. However, the two processes are commonly associated.

Offset drainages—Offset drainages are perhaps the most conspicuous evidence of recent movement along a strike-slip fault. It is important to note that not all bends in stream channels are fault related; additional lines of evidence are necessary to prove that a stream channel was offset by fault motion. Notable examples include Bird Creek in the Hollister Hills State Vehicular Recreation Area, Coyote Creek (along the Calaveras Fault between Coyote Reservoir and Anderson Reservoir near Morgan Hill), and Sanborn Creek in Sanborn County Park (described in chapter 6 of this guidebook).

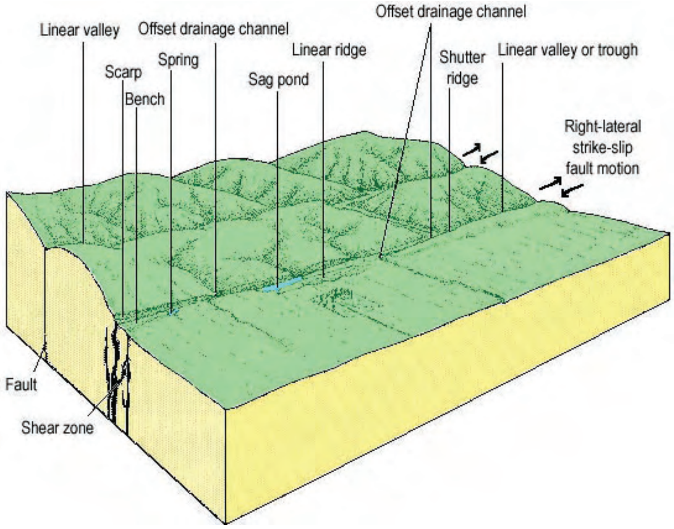


Figure 1-9. Geomorphic features associated with the San Andreas Fault system in California (after Vedder and Wallace, 1970).

Beheaded stream channels—Streams draining across an active strike-slip fault trace may be captured by an adjacent stream. With loss of its water supply or a source of sediments, the older channel will remain as a beheaded stream channel as fault motion continues. Examples can be seen at Sanborn County Park. Offset and beheaded streams are also called deflected drainages.

Linear troughs—The San Andreas Fault Zone ranges in width from a few feet to about almost a mile. Both tectonic extension and the erosion of sheared and softer rock along the fault zone result in the development of linear troughs along the San Andreas Fault. Linear troughs are typically valleys bounded by linear fault scarps. On many U.S Geological Survey topographic maps these linear troughs are labeled "San Andreas Rift Zone." Notable examples in the San Francisco Bay region include the San Andreas Rift Valley at Crystal Springs and San Andreas reservoirs along I-280, Olema Valley and Tomales Bay at Point Reyes National Seashore, and Coyote Creek along the Calaveras Fault between Gilroy and Morgan Hill in southern Santa Clara County.

Linear drainages—A stream drainage that follows the trace of a fault. Stream alignment may be a result of strike-slip fault motion or the erosion of sheared and pulverized rock along the fault trace. Bay Area examples include upper Stevens Creek Canyon in the Santa Cruz Mountains and Olema Creek at Point Reyes National Seashore.

Linear scarps—Linear scarps may form where there is a vertical component of offset along a fault (either normal or reverse). Linear scarps may also form when preferential erosion removes softer bedrock or soil along one side of a fault.

Sidehill benches—Both recent fault activity or erosional differences of bedrock lithology across a fault may produce sidehill benches and associated linear scarps. Sidehill benches may also form from slumping that may or may not be associated with faulting.

Linear ridges—A linear ridge is a long hill or crest of land that stretches in a straight line. It may indicate the presence of a fold or fault. If it is found along a strike-slip fault it may be a shutter ridge or a pressure ridge.

Shutter ridges—A shutter ridge is a ridge formed by vertical, lateral, or oblique displacement on a fault that crosses an area having ridge and valley topography, with the displaced part of the ridge "shutting in" the valley. Shutter ridges typically are found in association with offset or deflected streams.

Pressure ridges—A pressure ridge is a topographic ridge produced by compressional bends or stepovers along a strike-slip fault zone (fig. 1-10). Pressure ridges can be shutter ridges and can occur on one or both sides of a fault or within a fault zone.

Closed depressions (pull-apart basins)—Closed depressions can form where extensional bends or stepovers occur along a strike-slip fault zone (see fig. 1-10). A surface depression will form along a fault where down warping of the surface occurs, such as from a developing fold or a fault-bounded graben. If the pull-apart can hold water, even temporarily, it is called a sag pond.

Linear vegetation contrasts—The natural landscape along a fault zone may show changes in vegetation across the fault trace. This typically reflects changes in the physical character of soils associated with the weathering of the underlying bedrock. For example, well-drained alluvium might be overlain by grass. Oak woodlands may prefer a soil formed on weathered shale that can retain more water, or a conifer forest will more likely develop where more acidic conditions occur in sandy soils derived from the weathering of sandstone. Manzanita often thrives in areas underlain by serpentinite. In many places throughout the San Francisco Bay region, vegetation contrasts are perhaps the most revealing evidence of the location of faults. However, other historic events and land uses may be responsible for linear vegetation contrasts, such past agricultural activity, fires, and logging.

Regional-Scale Features—Regional scale features associated with the San Andreas Fault system are typically too big to observe from the ground and require observation from maps, aerial photographs, and satellite images. From the air, the San Andreas Fault often appears as a linear trace across the landscape even though it might not be obvious to observers on the ground. The San Andreas Fault is not perfectly straight, but bends gently in some locations. Where the fault bends to the left (where observed from the south), enhanced compressional forces produced uplifts like the Santa Cruz Mountains and Gavilan Range. Where the fault bends to the right the land's surface is downwarped, such as in the region around San Francisco Bay where the San Andreas Fault runs under the Pacific Ocean. In areas where the fault is relatively straight there may be little or no relief such as in the region around the Carrizo Plain in central California. The complexity of the interconnected fault system in the San Francisco Bay region can arguably be responsible for nearly all the prominent landscape features. The Santa Cruz Mountains can be viewed as a great pressure ridge along the San Andreas Fault, and the Diablo Range and East Bay Hills are pressure ridges along the Calaveras and Hayward Faults of the East Bay fault system. In many places, thrust faults splay away from these major faults (at depths of many miles) and extend laterally into surrounding areas. Some thrust faults are exposed

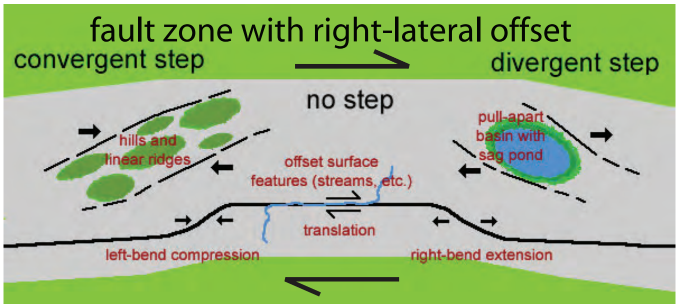


Figure 1-10. Geomorphic features associated with divergent and convergent step in a fault zone. Step faults are closely spaced, usually parallel faults over which the total displacement within a fault zone is distributed. Active faults (black) are shown within a broader fault zone (gray). These examples are in a right-lateral strike-slip fault zone like the San Andreas Fault. Arrows indicate relative movement.

along the range fronts or extend into the basin areas around San Francisco Bay and along the Santa Clara Valley. Some thrust faults (called “blind thrusts”) may not be exposed at the surface and could potentially produce severe earthquake damage to urbanized areas.

Geomorphic Features Associated with Landslides

Landslides produce many of the same geomorphic features as those associated with faults of tectonic origin (fig. 1-11). In fact, it is often difficult to differentiate tectonic faulting from landsliding, which is a result of gravitational forces. These different processes are defined below:

Landslide—A general term covering a wide variety of mass-movement landforms and processes involving the downslope transport, under gravitational influence, of soil and rock *en masse*. Usually the displaced material moves over a relatively confined zone or surface of shear. Landslides have a great range of morphologies, rates, patterns of movement, and scale. Their occurrence reflects bedrock and soil characteristics and material properties affecting resistance to shear. Landslides are usually preceded, accompanied, and followed by perceptible creep along the surface of sliding and (or) within the slide mass. Slumps, debris flows, rockfalls, avalanches, and mudflows are all various forms of landslides. A slump is the downward slipping of a mass of rock or unconsolidated material, moving as a unit, usually with backward rotation on a more or less horizontal axis parallel to a slope or cliff from which it descends. Slumps typically form a fault-like escarpment and may occur at the head of a landslide.

Rockfall—The relatively free falling or precipitous movement of a newly detached segment of bedrock of any size from a cliff or very steep slope; it is most frequent in mountainous areas during spring when there is repeated freezing and thawing of water in cracks of rock. Movement may be straight down or in a series of leaps and bounds down the slope; it is not guided by an underlying slip surface.

Debris flow—A moving mass of rock fragments, soil, and mud in which more than half of the particles being larger than sand size (otherwise it would be a mudflow) and with 70 to 90 percent of the material consisting of sediment (the rest is water and trapped gasses). Slow debris flows may only move a few feet per year, whereas rapid ones can reach speeds greater than 100 miles per hour. Debris flows can display either turbulent or laminar flow characteristics.

Debris flood—A typically disastrous flood, intermediate between the turbid flood of a mountain stream and a debris flow, ranging in sediment load between 40 to 70 percent.

Creep—The slow, more or less continuous downslope movement of surface materials (mineral, rock, and soil particles) under gravitational stresses. Trees on a slow creeping hillside tend to gradually realign themselves upward as the massive root stocks slowly rotate downhill over time. Contrast this with earthquake terminology, where creep is the slow, more or less continuous movement occurring on faults due to ongoing tectonic deformation.

Plant Communities of the San Francisco Bay Region

Dense plant cover in the Santa Cruz Mountains makes geologic mapping difficult. However, variations in both plant cover and surface topography reveal patterns that often help make geologic interpretations possible, even where bedrock is not exposed (fig. 1-12). This guide to plant communities in the San Francisco Bay region is included here to assist locating geologic features in the field based on vegetation and soil associations

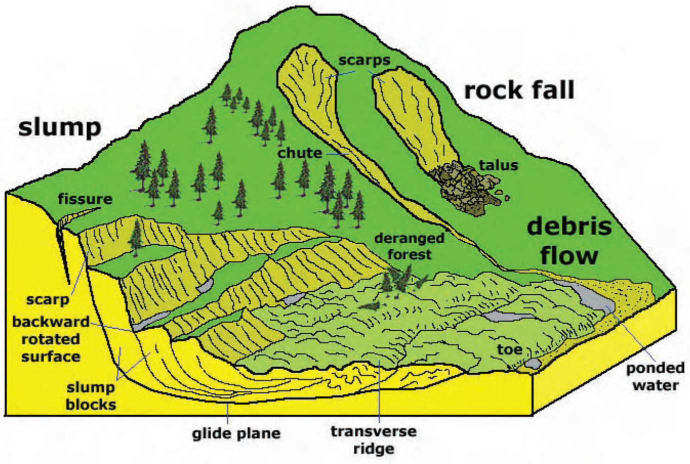


Figure 1-11. Landscape features associated with landsliding and slumping.

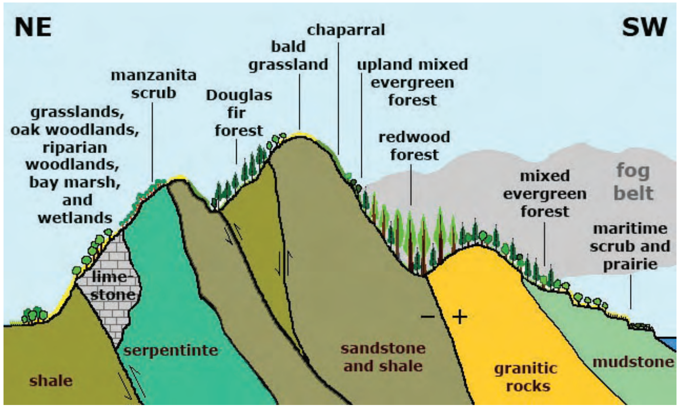


Figure 1-12. Plant habitats of the Santa Cruz Mountains. The diagram also shows the generalized bedrock character of the Santa Cruz Mountains. Arrows show thrust faults, and the –\+ designation shows the San Andreas Fault with its right-lateral offset (+ is toward the viewer; – is away). Note that vegetation characteristics are also influenced by slope angle and aspect (that is, north or south facing slopes), precipitation, elevation, land-use history, and other factors.

Figure 1-13. Maritime scrub habitat (or maritime chaparral). Beach, sea cliffs, dunes, estuaries, and marine terraces support a mixed coastal shrub, deciduous meadows, grassland, riparian, marsh, and other habitats. Northern California's coast is a highly moderated climate (neither hot nor cold), and is characterized by salt tolerant species and semiarid conditions. The habitat is typically established on sandy soils on elevated terraces or stabilized dunes. Monterey cypress groves commonly occur alongside maritime scrub. Higher winter precipitation yields a bounty of annual and perennial wildflowers. Summer days are often fog bound. Fall is typically sunny but very dry. Much of the coastal prairie habitat on the marine terraces has been lost to agricultural activity and development. This view is of Cove Beach at Año Nuevo State Park.

Figure 1-15. Mixed evergreen forest. The name mixed evergreen forest best applies to the diverse forests that cover much of the upland areas of the Santa Cruz Mountains. Species from nearly every other type of floral habitat can be found interspersed in areas with complex topography underlain with a mix of bedrock and soils. Mixed evergreen forest includes oaks, redwoods, Douglas fir, pines, chaparral, laurel, madrone, and other trees and shrubs. The name, mixed evergreen forest, is useful where other habitat names don't apply well. This view is at Calero County Park in Santa Clara County.

with bedrock lithologies. Bedrock and soil associations are perhaps as important as slope and moisture aspects in the establishment of plant communities. However, human impacts and fire history also define the character of the plant cover. Common plant communities (or habitats or ecosystems, depending of usage of the terminology) in the region are presented below (figs. 1-13 through 1-25). Habitat names presented here follow National Audubon Society, 2002; Schoenher, 1992, and local usage in San Francisco Bay regional parks.

Precipitation is highly variable across the Santa Cruz Mountains. Nearly all precipitation falls in the late fall to early

Figure 1-14. Coastal prairie habitat. Semiarid conditions along sections of the Northern California coast support grassland prairies that host a variety of flowering sedges and grasses. Yellow brush lupines and poison oak are among perennials that flourish on coastal dunes. This view shows the coastal prairie in the Tule Elk Reserve in Point Reyes National Seashore near Tomales Point.

Figure 1-16. Coastal redwood forest. Coastal redwood groves thrive in the coastal "fog belt" that extends from the coastal valleys to the crest of the northern Santa Cruz Mountains. These areas receive ample winter precipitation and as much as 12 inches (30 cm) of summer precipitation derived from fog. Most of the coastal redwoods were cut in the late 19th and early 20th century, but second growth forests are thriving in many areas. Large groves of ancient trees can be seen at Henry Cowell State Park in Santa Cruz County (shown in this view), Big Basin State Park (Santa Cruz and San Mateo Counties), and Muir Woods (Marin County).

Figure 1-17. Upland evergreen forest. Mixed evergreen forest (with common bay laurel and madrone), yellow pine, scrub oak, chaparral, manzanita, and a variety other shrubs grow in upland areas. Thicker patches of growth occur around hillside springs and drainages. This view is along Loma Prieta Avenue in Santa Cruz County in the upland area near Loma Prieta Peak.

spring (November to April) and during occasional late summer storms. Forests in the fog belt generate precipitation by trapping moisture with foliage (redwoods and Douglas fir do this). The highest areas within the Santa Cruz Mountains receive as much as 60 inches (150 cm) of precipitation annually, with only a small amount as snow in the winter. The coast receives 15 to 20 inches (38 to 40 cm) of rain and includes some salt concentration derived from wind-blown seawater spray. The driest parts of the San Francisco Bay region are in the central Santa Clara Valley and around southern San Francisco Bay, where precipitation averages less than 8 inches (20 cm) per year. Northeast facing slopes are cooler and wetter than south and west facing slopes, and slope aspect is typically reflected by vegetative cover.

The weathering of bedrock produces characteristic soils that influence vegetative cover. Coastal California is well known for it unique flora and fauna associated with serpentinite terrane. Low calcium, a plant nutrient, and high magnesium and other metal concentrations from the weathering of serpentinite have a toxic effect on most plants. Plants that successfully adapted in these difficult serpentine conditions are often rare and unique to specific outcrop areas. Sandstone and conglomerate typically

Figure 1-18. Bald grassland. Grass-covered hilltops in the Santa Cruz Mountains are called balds. Windy, dry conditions and nutrient-depleted soils favor the development of grass cover in upland areas. This view is in Calero County Park in Santa Clara County.

Figure 1-19. Chaparral. Chaparral thrives on dry, south facing slopes with thin or well-drained soil. Chaparral habitat includes many species of shrubs adapted to summer drought conditions, with chamise being the most common plant. This shrub community is typically brown during the summer and fall autumnal drought season. Hillsides covered with chaparral will turn dark green with winter rains. Chaparral replaces burned Douglas fir and oak woodlands, and it will also burn well under drought conditions. This view is in Uvas Canyon County Park in Santa Clara County. Clouds in the distance hang over Loma Prieta Peak.

Figure 1-20. Douglas fir forest. Douglas fir forests grow in elevations above the coastal oak woodlands and on the north-facing slopes in upland canyons. Douglas fir forests typically grow more inland and at higher elevations than coastal redwoods. Oaks, laurel, madrone, and occasional spruce grow amongst the firs. Most of the old growth forests were cut during the late 19th and early 20th centuries. This view is along the San Andreas Rift Valley on upper Soquel Creek in Santa Cruz County. This regrowth forest is part of the Soquel Demonstration Forest and the Forest of Nisene Marks.

Figure 1-21. Oak woodlands and valley grasslands. Oak woodland habitats grow in the Coastal Ranges and the Sierra Foothills regions and thrive in semiarid conditions. Nearly 20 species of oaks, buckeye, poison oak, gray pines (or knob cone pines), and other drought tolerant plants share this habitat. Oak woodlands typically occur along with open grasslands and chaparral. This view is looking east from the top of Bald Mountain in the Sierra Azul Preserve toward Mine Hill in Almaden-Quicksilver County Park in Santa Clara County.

weather to produce well-drained soils, whereas shale weathers to produce clay-rich soil that retains moisture. Soils in upland areas tend to be depleted in nutrients, resulting in subdued vegetation or bald grassland areas. Steep slopes are prone to landslides and erosional effects of precipitation, so soils tend to be thin or poorly developed. Shallow water tables along streams or on flood plains allow phreatophytes (cottonwood, willow, and poplar) to flourish. Decaying vegetation, particularly in oak and evergreen forests, produce organic acids that weather bedrock and establish acidic soils. Limestone bedrock produces basic soils and terracotta (red clay) soil that, like serpentinite, also supports unique flora.

Figure 1-22. Manzanita scrub (or chaparral). Manzanita forest thrives in areas with serpentinite bedrock in foothills on both sides of the Santa Clara Valley (but is not limited to serpentinite terrane). This view is in Calero County Park in Santa Clara County. Mount Umunhum is in the distance.

Figure 1-23. Riparian habitat. Riparian woodlands along streams include sycamore, willow, cottonwood, oak, and a variety of shrubs. Where preserved, valley grassland habitat covers ancient alluvial fan deposits in valleys. Development, flood control, dams and water diversions, and past agricultural activity have heavily modified this habitat throughout the urbanized lowland areas around San Francisco Bay and the Santa Clara Valley. This view is looking east over Coyote Creek County Park toward El Toro Peak beyond Morgan Hill in Santa Clara County.

The character of vegetation of any particular area, however, may be a result of many different factors relating to the local history and land use. Much of the San Francisco Bay region was subjected to intense lumbering and grazing. Vegetation boundaries may reflect the location of old fence lines or property boundaries. Burn areas may go through a succession of different floral habitats in the period of a century. For

Figure 1-24. Bay wetlands. Coastal wetlands range from freshwater to brackish to marine conditions, and each subhabitat supports a different variety of fauna and flora. Most of the coastal wetlands and marshes (or baylands) around San Francisco Bay have been heavily disturbed or destroyed by salt production, urban growth, fill, and other human activities, but efforts are underway to restore some of them. This view shows stream- and spring-fed wetlands in Coyote Hills Regional Park near Fremont, California. Valley grasslands cover the hills in the distance. This area is one of the most arid regions in the San Francisco Bay region, averaging only 6 to 8 inches (15 to 20 cm) of precipitation per year.

Figure 1-25. Salt marsh. Brackish, marine, to hypersaline conditions can persist in this tidal-influenced habitat. In undisturbed areas tidal channels feed onto mudflats covered with saltbush that can become partly to complete submerged during high tides. Salt marshes can have some of the highest organic productivity anywhere. Pickleweed and other halophytes (salt-loving plants) thrive in the intertidal to supratidal zones. Rich plankton and invertebrate production in estuarine conditions support fish spawning, bird feeding and nesting activity, and marine mammal birthing and feeding grounds. Many of these areas have been highly modified by past human activity, but great efforts are being made to restore them throughout the San Francisco Bay region. This view is of Elkhorn Slough National Estuarine Research Reserve along the border between Santa Cruz and Monterey Counties. Loma Prieta Peak is in the distant center.

example, a large section of Douglas fir forest in the Santa Cruz Mountains near Lexington Reservoir burned in 1985. Today the same area is now dominantly chaparral habitat but may one day again be a Douglas fir forest. Historic grazing has taken a heavy toll on oak woodland habitats (now mostly replaced by grasslands). Agriculture, urban development, and the introduction of foreign species have changed or decimated riparian, lowland, and coastal wetland habitats. Fortunately, the combined effects of regional wealth and philanthropy, environmentalism, and an educated leadership have resulted in the conversion of large tracts of upland and coastal habitats to park and open space. Many hundreds of thousands of acres have been salvaged and set aside for watershed protection and ecosystem restoration and preservation.

Selected References

Bartow, J. Alan, 1991, The Cenozoic evolution of the San Joaquin Valley, California: U.S. Geological Survey Professional Paper 1501, 40 p.

Brown, R.D., Jr., 1990, Quaternary deformation, *in* Wallace, R.E., ed., The San Andreas Fault system, California: U.S. Geological Survey Professional Paper 1515, p. 83-113

Cruden, D.M. and Varnes, D.J., 1996, Landslide types and processes, *in* Turner, A K., and Schuster, R.L., eds., Landslides investigation and mitigation: Washington, D.C., Transportation Research Board, National Research Council, Special Report 247, p. 36-75.

Iacopi, F.R., 1969, Earthquake Country: Menlo Park, Calif., Lane Books, 160 p.

Irwin, W.P., 1990, Geology and plate-tectonic development, *in* Wallace, R.E., ed., The San Andreas Fault system, California: U.S. Geological Survey Professional Paper 1515, p. 61-80.

Jachens, R.C., Wentworth, C.M., and McLaughlin, R.J., 1998, Pre-San Andreas location of the Gualala Block inferred from magnetic and gravity anomalies, *in* Elder, W.P., ed., Geology and tectonics of the Gualala Block, northern California: Society of Economic Paleontologists and Mineralogists, Pacific Section, Book 84, p. 27-63.

Gilbert, G.K., 1908, The San Francisco earthquake and fire of April 18, 1906: U.S. Geological Survey Bulletin 324, 170 p.

Lawson, A.C., chairman, 1908, The California earthquake of April 18, 1906—report of the State Earthquake Investigation Commission: Carnegie Institution of Washington Publication 87, 2 vols.

McLaughlin, R.J., Clark, J.C., Brabb, E.E., Helley, E.J., and Colon, C.J., 2001, Geologic maps and structure sections of the southwestern Santa Clara Valley and southern Santa Cruz Mountains, Santa Clara and Santa Cruz Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map 2373, 5 sheets, scale 1:24,000 [http://geopubs.wr.usgs.gov/map-mf/mf2373/].

McNutt, S.R., and Sydnor, R.H., eds., 1990, The Loma Prieta (Santa Cruz Mountains), California, earthquake of 17 October 1989: Sacramento, California Division of Mines and Geology Special Publication 104, 142 p.

National Audubon Society, 2002, Field guide to California: Alfred A. Knopf, Inc., 447 p.

Schoenherr, Allan, 1992, A natural history of California: University of California Press, California Natural History Guides No. 56, 772 p.

Starratt, Scot W., 2001, ...And the fog will burn off by noon—a brief introduction to the weather of the San Francisco Bay Area, *in* Stoffer, P.W., and Gordon, L., eds., Geology and natural history of the San Francisco Bay Area—a field-trip guidebook: U.S. Geological Survey Bulletin 2188, p. 165-172 [http://geopubs.wr.usgs.gov/bulletin/b2188/].

Stoffer, P.W., 2002, Rocks and geology of the San Francisco Bay region: U.S. Geological Survey Bulletin 2195, 58 p. [http://geopubs.wr.usgs.gov/bulletin/b2195/].

U.S. Geological Survey, 2003, This Dynamic Earth website: [http://pubs.usgs.gov/publications/text/Farallon.html].

U.S. Geological Survey, 2004, Landslide types and processes: U.S. Geological Survey Fact Sheet 2004-3072 [http://pubs.usgs.gov/fs/2004/3072/fs-2004-3072.html].

U.S. Geological Survey, 2005, Putting down roots in earthquake country—Your handbook for the San Francisco Bay region: U.S. Geological Survey General Interest Publication 15, 31 p. [http://pubs.usgs.gov/gip/2006/16/].

Vedder, J.D., and Wallace, R.E., 1970, Map showing recently active breaks along the San Andreas and related faults between Cholame Valley and Tejon Pass, California: U.S. Geological Survey Miscellaneous Geologic Investigations Map I-574, scale 1:24,000.

Wallace, R.E., 1990, Geomorphic expressions, *in* Wallace, R.E., ed., The San Andreas Fault system, California: U.S. Geological Survey Professional Paper 1515, p. 15-58. [http://education.usgs.gov/california/pp1515/].

Wells, Ray E., ed., 2004, The Loma Prieta, California earthquake of October 17, 1989—geologic setting and crustal structure: U.S. Geological Survey Professional Paper 1550-E, 204 p.

Wentworth, C.M., Black, M.C., McLaughlin, R.J. and Graymer, R.W., 1998, Preliminary Geologic Map of the San Jose 30 x 60-Minute Quadrangle, California: U.S. Geological Survey Open-File Report 98-795 [http://pubs.usgs.gov/of/1998/of98-795/].

Wentworth, C.M., Jones, D.L., and Brabb, E.E., 1998, Geology and regional correlation of the Cretaceous and Paleogene rocks of the Gualala Block, California, *in* Elder, W.P., ed., Geology and tectonics of the Gualala Block, northern California: Society of Economic Paleontologists and Mineralogists, Pacific Section, Book 84, p. 3-26.

2. Field-Trip Guide to the Hollister and San Juan Bautista Area

Trip Highlights: San Andreas Fault, Calaveras Fault, Mission San Juan Bautista, manmade structures damaged by earthquake creep, Salinian Basement Complex, Fremont Peak, marble, granitic rocks, fault scarps, sag ponds, offset streams, shutter ridges, vegetation contrasts

This field trip provides access to well-known fault-investigation sites in the southern Santa Clara Valley region. Field trips stops include fault scarps and offset manmade and natural landmarks along the Calaveras and San Andreas Faults, sag ponds, and bedrock exposures in the Salinian basement complex west of the San Andreas Fault. The field trip begins at the Hollister exit on Highway 101 on Highway 25 (fig. 2-1). **Drivers, please note that the highways are busy along these routes; drive cautiously and defensively**! Stops 1 to 4 are modified from Harden and others (2001). Stop 5 is a visit to the San Andreas Fault at Mission San Juan Bautista. Stops 6 and 7 involve driving up to Fremont Peak State Park (where camping is available in season). Stops A to C include an optional extension of the field trip to stops along the San Andreas Fault east off Highway 101 along Anzar Road, at a quarry in Aromas, and to the fault at Pajaro Gap. A very useful resource for this field trip is the Geologic Map of the Monterey 30’ x 60’ Quadrangle and Adjacent Areas, California by Wagner and others (2002). It is available from the California Geological Survey.

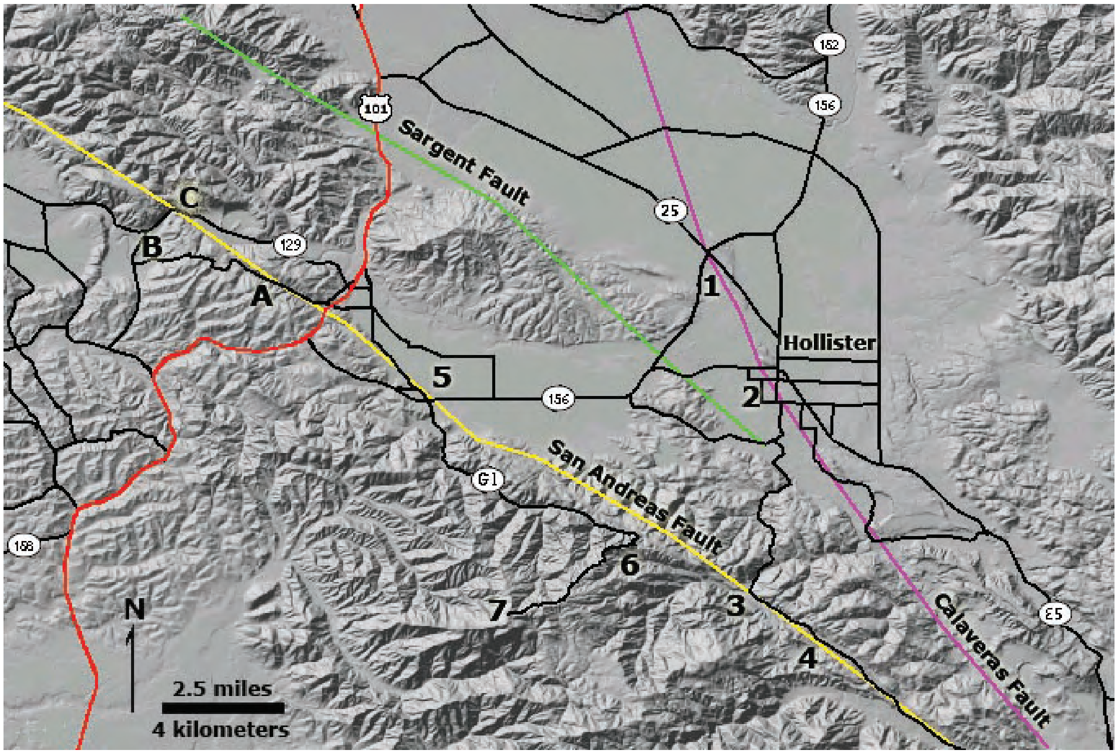


Figure 2-1. Field-trip stops include two along the trace of the Calaveras Fault in Hollister (1 and 2), stops along the San Andreas Fault at the Hollister Hill State Vehicular Recreation Area (3), the Cienega Valley (4), the mission at San Juan Bautista (5), and overlook areas along San Juan Canyon Road [G1] (6), and Fremont Peak State Park (7). An optional field trip in the vicinity is west of Highway 101 to Anzar Road (A), an active quarry in the Aromas area (B), and Pajaro Gap (C); however, these last stops are not recommended for children, large groups, or at any time other than early on a weekend morning when traffic might be light on Highway 129. Earthquake faults in the vicinity include the San Andreas Fault (yellow), the Calaveras Fault (purple), and the Sargent Fault (green); many other known, as well as unmapped or unknown, faults exist in the region.

Road Log to Hollister, Cienega Valley, and San Juan Bautista Area

Distance	Description
0.0	Exit from Highway 101 south onto Highway 25 south toward Hollister. **Reset the odometer mileage to zero.** The Hollister area has experienced extensive development during the housing boom of the 1990s. However, numerous farms are still actively providing strawberries, garlic, tomatoes, salad greens, and seed nurseries for flowers.
8.5 mi (13.7 km)	Traffic light at intersection of Route 156.
9.0 mi (14.4 km)	**Stop 1 (rolling stop)—Pressure ridges along the Calaveras Fault** (see stop description below). The landscape features seen here are best viewed by slowly driving from this point onward into Hollister. However, be cautious of traffic behind you! A small, dirt section-boundary road on the right offers a photo stop; however, do not attempt to stop if farm vehicles are present or if the ground is wet. Keep out where posted and do not walk in crop fields.
11.0 mi (17.7 km)	A water tank on the right is built on a pressure ridge along the Calaveras Fault.
11.5 mi (18.5 km)	At a stoplight, Highway 25 becomes San Benito Avenue. Continue south into downtown Hollister. Prepare to turn right on 6th Street. Proceed west for two blocks to Dunne Park on the corner of 6th Street and West Street.
12.3 mi (19.8 km) **0.0 mi (0.0 km)**	**Stop 2—Dunne Park** (see stop description below). Restrooms are available here. Offset from fault creep along the trace of the Calaveras Fault can be observed throughout the neighborhood around the park. After the stop, proceed east on 6th Street. **Reset the odometer mileage to zero** at corner of 6th Street and San Benito Avenue.
0.5 mi (0.8 km)	Downtown Hollister.
0.7 mi (1.1 km)	San Benito Avenue becomes Nash Road; continue straight at the light following signs to the Hollister Hills State Vehicular Recreation Area.
1.6 mi (2.6 km)	Turn right (west) at stop sign (Union Road). Cross the bridge over the San Benito River.
1.7 mi (2.7 km)	Immediately after crossing the bridge, turn left (south) on Cienega Road.
3.2 mi (5.1 km)	Stop sign. Continue to the right on Cienega Road. The road winds uphill through an area affected by active landslides in Tertiary sedimentary rocks.
6.5 mi (10.4 km)	Cross Bird Creek.
7.0 mi (11.3 km)	Turn right at Hollister Hills State Vehicular Recreation Park. The San Andreas Fault runs through the valley on the left.
7.1 mi (11.4 km)	Pass the park ranger station. A day-use fee per vehicle may be required. Proceed on the unpaved road into the park.
7.9 mi (12.7 km)	Turn a sharp left and proceed uphill to the picnic tables on the south end of Radio Ridge.
8.0 mi (12.8 km)	**Stop 3—Radio Ridge** (see stop description below). Restrooms are available at this stop. After this stop, return past the ranger station to the park entrance.
8.8 mi (14.2 km)	Park entrance. Turn right (south on Cienega Road).
9.9 mi (15.4 km)	Vineyard School, on the right, is built on the San Andreas Fault.
10.6 mi (17.0 km)	A sag pond along the fault is on the left. A local oral history account is that this pond drained after the 1906 earthquake.

Continued.

10.8 mi (17.4 km) **0.0 mi (0.0 km)**	**Stop 4—DeRose Winery** (see stop description below). The winery building was built on the San Andreas Fault and is slowly being torn apart by ongoing fault creep. After the stop, return north toward Hollister on Cienega Road. **Reset the odometer mileage to zero**.
6.0 mi (9.7 km)	Bear left at the "Y" intersection and continue on Cienega Road.
7.5 mi (12.1 km)	Turn left (west) onto Union Road.
11.1 mi (17.9 km)	Turn left (west) onto Highway 156.
15.2 mi (24.5 km)	Turn right onto The Alameda into the town of San Jan Bautista. The San Juan Bautista Mission is one block to the right of The Alameda in downtown. Turn right on Washington Street and start looking for parking. There are many excellent restaurants along The Alameda. Field-trip planners might consider ample time to enjoy a meal and a tour of the mission area.
15.5 mi (24.9 km)	**Stop 5—San Juan Bautista State Historical Park** (see stop description below).

Stop 1 (rolling stop)—Pressure Ridges Along the Calaveras Fault Near Hollister

Stop highlights: Fault scarps, pressure ridges, and sag ponds along the Calaveras Fault

Low, linear escarpments reveal the main fault trace of the Calaveras Fault and other splay faults throughout the Hollister area. Examples of these pressure ridges and fault scarps can be seen along Highway 25 between the intersection of Highway 152 and downtown Hollister (figs. 2-1 and 2-2). **(Driving warning: Highway 25 is a busy highway, and it is not recommended to stop along the road, particularly if more than one vehicle is on the field trip.)** The Calaveras Fault is part of the greater San Andreas Fault system in the San Francisco Bay region. The Calaveras Fault splays away from the San Andreas Fault about 10 miles south of Hollister, near the town of Paicines, California. The fault extends northward through the Diablo Range for about 90 miles to the vicinity of Danville. The southern segment of the Calaveras Fault (between Paicines and San Felipe Lake along Highway 152) is one of the fastest creeping fault segments in the San Francisco Bay region. Historic surface measurements show that the fault is creeping in the range of 0.4 to 0.7 inches (11-19 mm) per year (Kelson and others, 2004). Geophysical investigations show that as much as 108 miles (174 km) of offset has occurred along the Calaveras Fault in the past 12 million years. This translates to roughly 0.54 inches (13.7 mm) of offset per year (McLaughlin, and others, 1996). Strike-slip deformation is partitioned between the northern Calaveras, the

Figure 2-2. Escarpment and linear ridge (pressure ridge) on the Calaveras Fault along the east side of Highway 25, north of downtown Hollister.

Figure 2-3. A sag pond and low, linear scarp along a second strand the Calaveras Fault of the west side of Highway 25, north of downtown Hollister. This view was taken in the same location as figure 2-2.

Hayward, and other faults that splay from the central segment of the Calaveras Fault in the vicinity of Calaveras Reservoir.

Stop 2—Dunne Park, Hollister

Stop highlights: Creeping trace of the Calaveras Fault; offset curbs, walls, buildings, and other damaged infrastructure

The Hollister area experienced damage from both the Great 1906 San Francisco earthquake and 1989 Loma Prieta earthquake. The town also experienced minor damage from earthquakes on the Calaveras Fault—the 1979 Coyote Lake earthquake (M 5.8) and the 1874 Morgan Hill earthquake (M 6.3). The Calaveras Fault runs through the urban heart of Hollister. Dozens of residential homes are built on or immediately adjacent to the active creeping trace of the fault, and damage from fault motion can be traced from block to block both north and south of Dunne Park. Cracks and offset sidewalks, curbs, walls, and buildings can be seen along every street and alley (fig. 2-4). Although local residents are probably accustomed to people observing fault damage, it is extremely important that field-trip participants be warned not to walk on lawns or photograph homes or people without permission. Limit walking to public sidewalks, alleys, or streets without disturbing residents. California laws relating to earthquake damage and repair to existing homes along active faults have put an extra financial burden on residents along the fault zone; some are quite vocal and deserve to have their opinions respected. All the homes in this neighborhood were built before modern seismic regulations were enacted.

Stop 3—Hollister Hills State Vehicular Recreation Area

Stop highlights: Rift valley of the San Andreas Fault, offset stream, shutter ridges, and vegetation and bedrock contrasts on opposite sides of the fault

The Hollister Hills State Vehicular Recreation Area consists of 6,627 acres dedicated to off-road vehicle activities. The north section of the park has more than 60 miles of trails for motorcycles, and the southern section is limited to 4-wheel-drive vehicles. It is operated by the State Department of Parks and Recreation. An entrance fee is required to use the park (field-trip planners might call in advance to inquire about an educational group access waver). The park straddles the San Andreas Fault. Radio Ridge is a low, linear hill in the middle of the broader linear valley of Bird Creek. A picnic area on the ridge provides views of the surrounding landscape (figs. 2-5 and 2-6). Bird Creek is an offset (or deflected) stream. The stream's headwater region is on the west side of the fault. The lower part of the stream drainage is confined to a canyon through a shutter ridge on the east side of the fault. The steep, chaparral-covered slopes on the southwest side of the valley are underlain by crystalline basement rocks (granitic plutonic rocks of Mesozoic age and Paleozoic and Mesozoic gneiss, schist, and marble of the Fremont Peak area that predate the granitoid intrusions). The northeast side of the valley is dominated by oak woodlands and grasslands. The bedrock in this area consists of late Tertiary (Miocene and Pliocene)

Figure 2-4. View looking east along an offset wall and sidewalk on 6th Street in Hollister adjacent to Dunne Park. The park itself preserves a low hill that is a scarp of the Calaveras Fault. The low area within the park west of the scarp was in part a sag pond prior to development of the area.

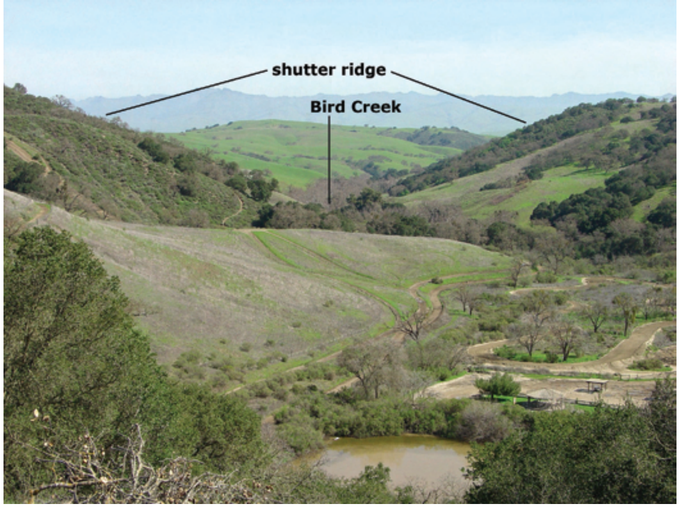


Figure 2-5. This view is looking east from Radio Ridge to the gap where Bird Creek (a fault offset stream) cuts through a shutter ridge and drains toward the Hollister Valley. Bird Creek carved a linear valley along the San Andreas Fault Zone. The rift valley continues as the Cienega Valley south of the Hollister Hills State Vehicular Recreation Area.

Figure 2-6. This view looks toward the southeast from Radio Ridge up the San Andreas Rift Valley. The active trace of the San Andreas Fault runs along the right side of the grassy area in the valley.

sedimentary rocks of marine and nonmarine origin. Both fossil shell material and lignite (soft coal) occur amongst beds of sandstone, shale, and mudrocks mostly of the Pliocene-age Etchegoin Formation.

Stop 4—DeRose Winery

Stop highlights: Offset drainage ditch and building on the San Andreas Fault, sag ponds, San Andreas Rift Valley

The DeRose Winery claims to be the oldest existing winery in California. A French immigrant, Theophile Vaché established a vineyard in Cienega Valley and began selling wine in San Juan Bautista starting in 1854. Cienega means marsh in Spanish and the valley is appropriately named after the natural sag ponds that exist along the San Andreas Fault here. The vineyard has a long history of wine production and has survived several changes in ownership, major earthquakes, and prohibition. The large production facility has an interesting history because it was built directly on the trace of the creeping section of the San Andreas Fault. Evidence of damage to the building and infrastructure along the trace of the fault are clearly visible. Perhaps of greatest significance is an offset cement-lined channel that was built in the late 19th century. It now displays about 3 feet (1 meter) of right-lateral offset (fig. 2-7). The vineyard building itself is offset by the fault. Cracks in the parking area and offset walls and bent boards can be seen on both sides of the building. The site was designated a National Natural Landmark in 1965. The National Park Service's landmark description states that one-half of a Cienega Winery building moved 8 inches in a span of 9 years. The commerative National Natural Landmark plaque is attached to a broken and offset wall inside the winery building. A tour of the facility may be arranged by calling the vineyards in advance.

Figure 2-7. This cement-lined drainage ditch on the south side of the DeRose Vineyards shows offset from creep along the San Andreas Fault. The drain was probably constructed before the 1906 earthquake.

Stop 5—San Juan Bautista

Stop highlights: Escarpment of the San Andreas Fault, a historic Catholic mission damaged by the 1906 earthquake

San Juan Bautista is one of the oldest towns in California and has rich history in connection to its cultural history and to historical earthquakes and disaster (San Juan Bautista, 2005). The location chosen to build the San Juan Bautista Mission couldn't have been better in the eyes of the Franciscan fathers when they founded it on June 24, 1797. A low ridge above the broad floodplain of the San Benito River would provide a commanding view of agricultural activities (fig. 2-8). In time, the mission and settlement would host commerce traffic along the El Camino Real (the King's Highway) that passed along the base of the hill next to the mission site. This is the highway that connected all of the California missions and later served as one of California's major stage and wagon roads. The town site had great potential to become a significant population center in California. However, many things happened over the course of time that prevented the town from growing. To begin with, little did they know that the straight hill next to the mission site was the escarpment of the San Andreas Fault!

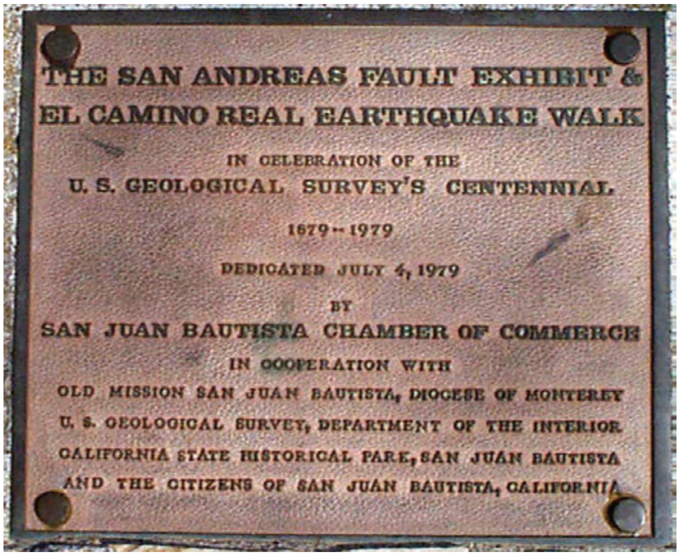
The onset of trouble began before the mission was even built. In October 1798 the shaking from an earthquake was so bad that the missionaries slept outside for the whole month. As many as six strong earthquakes occurred in a single day, leaving many huge cracks in the ground and damaging newly constructed buildings. Shortly afterward in 1803, a newly constructed church building was destroyed by an earthquake. However, the town population was growing quickly. The "modern" mission was designed to accommodate a thousand people and, hopefully, to withstand significant earthquake

Figure 2-8. The San Juan Bautista Mission. The trace of the San Andreas Fault runs along the foot of a historical grandstand (painted green) along the El Camino Real (at the base of the stairs). The historic road runs along the San Andreas Fault scarp through the northeast side of town.

shaking. The developing mission experienced its next damaging earthquakes in 1836 and 1838. The 1836 Hayward earthquake may have actually had its epicenter along the San Andreas Fault near San Juan Bautista. The 1838 earthquake occurred along the Peninsula section of the San Andreas Fault. In the period before the 1849 Gold Rush, the town of San Juan Bautista had a population of several hundred Californios (Spanish descendants) and a large Native American population. The San Juan Valley was the home of the Mutsun Indians. At one time some 1,200 Indians lived and worked at this mission (as many as 5,000 Mutsun Indians are buried in the town cemetery). The Gold Rush brought a flood of northern European and English-speaking settlers to the region. However, these new immigrants largely avoided the Spanish-speaking town and established Hollister which would soon eclipse San Juan Bautista as the economic center of San Benito County. The transition happened on the heals of disaster.

In 1869 a smallpox outbreak occurred in San Juan Bautista. A local resident observed that a guest at a town meeting had symptoms of the disease. They immediately tried to quarantine the sick person but it was too late. The entire community was soon quarantined under Marshall Law; if someone attempted to flee they would be shot. When the outbreak was over, nearly a third of the town's residents were dead, and a community of Native Americans (laborers) nearby was completely wiped out by the disease. Six months later, a fire swept through much of the downtown area. The combination of the two events crippled the town for years. Then the 1906 earthquake struck. The mission was nearly destroyed along with many of the business buildings and residences throughout the town. The next crushing blow came when the town was bypassed by the railroad which went instead through Hollister. In addition, much of the land around could not be developed for fear of flooding from the nearby San Benito River.

In 1949, the Hearst Foundation financed efforts to restore the mission to its original form. However, repair of damage to the mission from the 1906 earthquake was not completed until the 1970s. In contrast, the 1989 Loma Prieta earthquake caused only minor damage to the mission. However, in many respects the historic town has been "saved" by its misfortune. Today the town retains much of its historic architecture, culture, and charm. It has a thriving restaurant and shopping district on the Alameda (3rd Street), and the active historic Catholic mission and museum area on 2nd Street are part of the San Juan Bautista State Historical Park.



THE SAN ANDREAS FAULT EXHIBIT &
EL CAMINO REAL EARTHQUAKE WALK
IN CELEBRATION OF THE
U. S. GEOLOGICAL SURVEY'S CENTENNIAL
1879 -- 1979
DEDICATED JULY 4, 1979
BY
SAN JUAN BAUTISTA CHAMBER OF COMMERCE
IN COOPERATION WITH
OLD MISSION SAN JUAN BAUTISTA, DIOCESE OF MONTEREY
U. S. GEOLOGICAL SURVEY, DEPARTMENT OF THE INTERIOR
CALIFORNIA STATE HISTORICAL PARK, SAN JUAN BAUTISTA
AND THE CITIZENS OF SAN JUAN BAUTISTA, CALIFORNIA

Figure 2-9. A brass plate on the San Juan Bautista Mission grounds commemorates the 100th anniversary of the U.S. Geological Survey (USGS). The original exhibit contained a USGS seismograph and seven stops along the "El Camino Real Earthquake Walk." Only this brass plaque remains today.

A trip to the mission plaza and grounds offers an excellent view of the San Andreas Fault escarpment along the northeast side of the mission. Hints of modern offset on the fault can be seen in several locations in the San Juan Bautista area. Cracks in old pavement can be seen along back roads that cross the San Andreas Fault south of Highway 156. In addition, a visible break in a wall can be seen outside of the Faultline Restaurant just southeast of the mission. However, actual fault motion can only be inferred from these features without more sophisticated precision survey measurements across the fault over time.

Road Log to Fremont Peak State Park (Optional Field-Trip Extension)

Distance	Description
0.0 mi (0.0 km)	At the intersection of The Alameda (in San Juan Bautista) and Highway 156, proceed south on San Juan Canyon Road following signs to Fremont Peak State Park. (The Alameda becomes San Juan Canyon Road south of the intersection.) The drive is about 11 miles. **Reset trip mileage to zero** at the intersection of Highway 156 and San Juan Canyon Road.
0.2 mi (0.3 km)	Bear to the left to stay on San Juan Canyon Road. The road to the right is the Old Stage Road that connects San Juan Bautista to Salinas Valley. A sign at the intersection states that the distance to Fremont Peak is 11 miles. Large barren outcrops of marine sandstone of Miocene age (Temblor Sandstone) crop out in the hills on both sides of the road. Pyroclastic volcanic rocks of Miocene age are mapped in the area but are not visible along the road.
5.0 mi (0.8 km)	A private picnic area owned by the Church of Jesus Christ of Later Day Saints (Mormon) is on the right. The picnic area is adjacent to a large abandoned granite quarry in the Salinian basement complex. Tailings from the quarry operations can be seen near the mouth of San Juan Canyon.
7.0 mi (km)	The road begins to ascend from San Juan Canyon. It passes very close to the San Andreas Fault Zone near the eastern-most point along the route, but nothing is apparent in the forested landscape except perhaps the character of the low divide to the left of the road where the fault crosses a saddle between drainage divides. Bird Creek drainage is to the south.
8.5 mi (13.7 km)	**Stop 6—Overlooks along San Juan Canyon** Road (see stop description below). Several small pulloffs are available along both sides of the road. The road ascends along a ridgeline that provides views of Bird Creek Valley to the east and Peak Canyon (with the Mormon camp quarry) to the west. After the stop continue uphill (west).
11.2 mi (18.0 km)	**Stop 7—Fremont Peak State Park** (see stop description below). Restrooms and camping are available here. Camp sites must be reserved in advance of the trip. After the stop, return to San Juan Bautista by the same route.

Stop 6—San Juan Canyon Road

Stop Highlights: Views of the rift valley of the San Andreas Fault, weathered granite, an abandoned granite quarry

San Juan Canyon Road runs south from downtown San Juan Bautista (across from where the Alameda intersects Highway 156). The road follows the historic stage route for a short distance before veering off to the left. At one time, this area was a Native American village where more than a thousand people may have lived. That village vanished after the smallpox outbreak in 1869 (see above) that completely annihilated the population. No obvious trace of the village remains.

San Juan Canyon Road extends for 11 miles (18 km) to near the summit of Gavilan Peak (now Fremont Peak in Fremont Peak State Park). The name, Gavilan, has been relegated to the entire range extending south from the San Juan Bautista area to the Pinnacles (at Pinnacles National Mounument). Most of the range is a great massif of Salinian crystalline basement (Mesozoic-age granitic rocks that have intruded older Paleozoic and Mesozoic metamorphic rocks). The Gavilan Range (also spelled Gabilan) is on the west side of the San Andreas Fault.

Near where the road enters San Juan Canyon, piles of abandoned gravel in the fields to the right side of the road are reminders of past mining activity in the area. Salinian granitic rocks and marble were mined locally for aggregate and probably cement. A large abandoned quarry is in the vicinity of the "Mormon camp" along the road. The road crosses the Vergeles Fault in the vicinity of the Mormon camp. The Vergeles Fault splays from the San Andreas Fault near where San Juan Canyon road makes a steep bend to the south and ascends from the valley along a ridgeline leading to Fremont Peak. The Vergeles Fault extends westward across the northern flank of the Gavilan Range and vanishes under the cover of Quaternary sediments along the Pajaro River Valley to the west of Highway 101.

While driving up San Juan Canyon Road the bedrock and vegetation changes as it crosses the Vergeles Fault. North of the fault the bedrock consists of Miocene-age volcanic rocks (not exposed due to weathering and plant cover) and older Tertiary sedimentary rocks. Massive outcrops of Vaqueros Sandstone (Oligocene age) occur throughout the hillsides along side of the road. These are the same rocks that crop out along Rocks Road and along Highway 101 south and west of San Juan Bautista (and at Castle Rock State Park in the Santa Cruz Mountains). In this section of the canyon, the hillsides are covered with a mixed oak and evergreen forest. On the south side of the Vergeles Fault the bedrock consists of weathered granitic rocks that are dominantly covered with chaparral on the upland south- and west-facing slopes.

Stop 6 is located along the road approximately 8.5 miles from Highway 156 on San Juan Canyon Road. Vehicles can pull off on the right side of the road onto two unpaved spur roads. Vistas are seen on both sides of the road in this area where the road follows the ridgeline. On the west side of the road, the view encompasses the abandoned quarry near the Mormon picnic area and the region around the southern Santa Cruz Mountains in the distance (fig. 2-10). This hard-rock quarry produced granitic aggregate and stone. The dominant rock types include granodiorite, garnet-bearing granitoid gneiss, and schist. On the south side of the road, the view encompasses the headwater region of Bird Creek in the Hollister Hills State Vehicular Recreation Area (fig. 2-11). The trace of the San Andreas Fault can be seen down the valley where the vegetation changes from chaparral (covering weathered granitic bedrock) to oak woodlands and grasslands growing on latest Tertiary-age sedimentary rocks on the east side of the fault. The trace of the fault extends into a rift valley southward into the Cienega Valley area.

Continue uphill; note the character of the weathered granitic bedrock and the light-colored quartz and aplite veins that protrude from the weathered rock. Also note the vegetation change where the road crosses from bedrock consisting of weathered granite to bedrock dominated by marble and other ancient metamorphic rocks.

Figure 2-10. An abandoned granite quarry near the "Mormon camp" on San Juan Canyon Road. The rock is mostly granitoid gneiss with some schist and intrusive dikes.

Stop 7—Fremont Peak State Park

Stop highlights: Vistas of Salinas and Santa Clara Valleys and Monterey Bay; Salinian Basement marble; lead mines

In 1846, Captain John C. Fremont and his company of U.S. surveyors climbed Gavilan Peak and built a hasty fortification of earth and logs, expecting stiff resistance from Mexican Californios. The peak area was known for its wide view of the region and small-scale lead mining activity. Fremont and his men had been allowed to spend the winter in California under the condition that they stay away from coastal settlements in the region. Fremont chose to ignore this decree, and reports reached the Mexican Governor of California, Jose Maria Castro, who was already concerned by the flood of non-Spanish speaking people into the region. The Governor sent troops to remove Fremont and his men. While waiting for the arrival of the troops, the defenders raised the United States flag over their fortification (the first time recorded in California). However, after several days of not-so-diplomatic negotiations, a battle still did not materialize. Probably because of their limited supplies of food and water on the mountain top, Fremont and his men grudgingly decided to break camp and head for Oregon.

Today, Gavilan Peak is called Fremont Peak and the summit area is incorporated into Fremont Peak State Park. The name, Gavilan, is now applied to the range extending from about Highway 101 southward to the Pinnacles National

Figure 2-11. View of the San Andreas Rift Valley in the vicinity of Bird Creek in the Hollister Hills State Vehicular Recreational Area. SAF is the San Andreas Fault. BC is the offset gap of Bird Creek Canyon. CF is the San Benito River valley and the location of the Calaveras Fault. DR indicates the Diablo Range in the southern Quien Sabe Range southeast of Hollister.

Monument area. Trails lead to the craggy summit of the mountain, and the park maintains a public campground (make reservations well in advance!). A radio facility is operated on one of the lesser peaks in the summit area. Also, the Fremont Peak Observatory Association maintains an observatory in the park. Many amateur astronomers come to the peak on the new moon each month.

Fremont Peak offers some interesting geologic observations. The summit area consists of a ridge of marble and dolomite that display interesting textural characteristics which are a source of long-standing discussions (fig. 2-12). The primary questions focus on whether the texture of the marble is a result of primary sedimentary structures (such as unusual layering typical of fossil algal stromatolites or stromatoporoids) or if the texture only represents secondary metamorphic foliation. (Foliation in marble is caused by recrystallization of minerals—calcite and dolomite—under high temperature and pressure; it gives the rock a layered appearance that is typically very different than that of its original sedimentary host rock). Early investigations suggested that the marble preserves calcitic crinoid column fragments of Paleozoic age. Other reports suggested that the rock is of Cretaceous age (closer to the age it underwent metamorphic alteration and intrusion). The rock was ultimately derived from the southern California region, where both Paleozoic carbonate rocks and Mesozoic intrusive rocks occur. The rock migrated northward along the San Andreas Fault and possibly other fault systems that predate the San Andreas. Fissures in the marble around the ridge top preserve cavernous travertine deposits and some cerussite (lead carbonate) deposits that were the target of early, small-scale mining operations (fig. 2-13). Prospect pits, shafts, and tunnels are scattered throughout the mountain top (mostly on nearby private land). It is recommended to stay out of the mines due to their instability and the potential of disturbing bats, rattlesnakes, and other wildlife that access them.

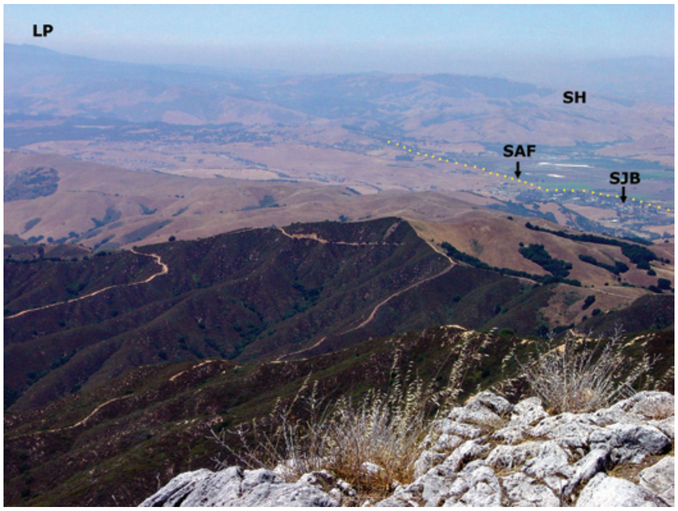


Figure 2-12. Fremont Peak is 3,169 feet in elevation. This north-facing view shows part of a marble outcrop in the foreground. The chaparral ecosystem in the midground overlies weathered granitic basement. The grasslands beyond the chaparral-covered slope consists Tertiary sedimentary and volcanic rock north of the Vergeles Fault. SJB is San Juan Bautista; SAF shows the linear escarpment of the San Andreas Fault. SH is the Sargent Hills. LP is Loma Prieta Peak where the San Andreas Fault crosses its southern (left) flank.

Figure 2-13. An old lead mine in the marble of Fremont Peak. Note that the barren bushes in and around the mine are poison oak.

Road Log to the Anzar Road and Pajaro Gap Area (Optional Field-trip Extension)

Distance	Description
0.0 mi (0.0 km)	This trip begins at San Juan Bautista Mission. Follow 2nd Street west from the mission.
0.4 mi (0.6 km)	Bear right on Monterey (proceed one block).
0.5 mi (km)	Bear left on San Juan Road. The escarpment of the San Andreas Fault vanishes in the fields northwest of the mission but emerges again along the low hills on the west side of San Juan Road.
2.4 mi (3.9 km)	Turn left on Anzar Road. The hill slope on the left side of the road is probably a fault scarp within system of local faults associated with the San Andreas Fault Zone.
3.6 mi (5.8 km)	Overpass of Highway 101.
3.7 mi (6.0 km)	Intersection of Anzar Road and Searles Road (frontage road for Highway 101). Continue straight on Anzar Road. **Note:** To get to Stop A from Highway 101, exit at Highway 129, toward Watsonville. (This exit is 40.9 miles south of the intersection of Highway 85 and Highway 101 in south San Jose.) Once off the highway ramp, proceed south on Searles Road. (Searles Road runs parallel to Highway 101 south.) Proceed south on Searles Road 0.7 miles to the intersection with Anzar Road. Turn right (west) on Anzar Road. Cracks in Searles Road located several hundred feet south of the intersection with Anzar Road are probably a result of fault creep along the San Andreas Fault.
0.0 mi (0.0 km)	**Stop A—Anzar Road** (rolling stop). **Reset the odometer mileage to zero** at the intersection of Searles and Anzar roads.
0.5 mi (0.8 km)	A sign along Anzar Road says: "Stevens Creek Quarry, Williams Pit: (408) 253-2512; Plant #2 - (831) 623-9555."
1.1 mi (1.8 km)	Cross Canyon Road. Note the forested, cliffy slope on the left side of the fault and the grass-covered slope on the right. Cattails mark the location of springs and sag ponds along the fault zone.
1.5 mi (2.4 km)	A small abandoned quarry is on the left.
1.9 mi (3.1 km)	Anzar Lake is on the left. This is one of the largest sag ponds on the San Andreas Fault in the region. The east side of the rift valley is forested with eucalyptus.
2.4 mi (3.9 km)	Forest Road on right. The road bends to the left (south) and ascends a hill into the eucalyptus grove along the west side of the San Andreas rift zone. The landscape in this region is underlain by Pliocene marine sediments and Quaternary alluvial (nonmarine) sediments. These sediments overly the granitic basement rocks.
2.8 mi (4.5 km)	The road crosses a large conveyor belt that carries crushed rock from the granite quarry to the processing plant and railroad terminal.
3.1 mi (5.0 km)	Cole Road to left; bear to the right and continue on Anzar Road.
3.5 mi (5.6 km)	Intersection of Anzar Road with Carr Avenue and Aromitas Road. (Aromitas is an unpaved shortcut to Stop B). However, continue west on Carr Avenue. The road crosses a low divide and descends into the village of Aromas.
5.2 mi (8.4 km)	Turn right onto Carpenteria Road.
5.4 mi (8.7 km)	Intersection of Carpenteria and Blohm Avenue. Continue straight on Carpenteria. Gas and food can be purchased in the small downtown area at the crossroads.

Continued.

5.6 mi (9.0 km)	Turn right on Quarry Road just before the railroad tracks.
6.1 mi (9.8 km)	Intersection of Aromitas Road and Quarry Road. Proceed north into the quarry.
6.4 mi (10.3 km) **0.0 mi (0.0 km)**	**Stop B—Aromas Granite Quarry** (see description below). Stop at the quarry entrance station before proceeding. Permission is required to enter the quarry, and mining activity may prevent access to the main pit. It is advisable to call for tour permission well in advance. After the stop, return to the intersection of Quarry Road and Carpenteria. Turn right (north) on Carpenteria and proceed across the railroad tracks. **Reset the mileage to zero**.
0.6 mi (1.0 km)	Turn right (east) on Highway 129. Highway 129 follows the valley of the Pajaro River.
1.4 mi (2.3 km)	**Stop C—San Andreas Fault at Pajaro Gap (rolling stop)** (see stop description below). **Please note!** Due to fast and heavy traffic on Highway 129, groups should not plan to stop at the bend in the road where the fault crosses the road. Rather, proceed to a small pulloff on the right near the Crittenden Railroad Bridge.
1.8 mi (2.9 km)	**Stop C (continued)—Crittenden Railroad Bridge** (see stop description below). An unpaved road on the right leads to a small parking area next to the Crittenden Railroad Bridge over the Pajaro River. The original railroad bridge was heavily damaged by the 1906 earthquake. **Please Note!** Do not attempt to walk on the bridge or the railroad tracks! Trains blaze through this area at high speeds and the sound of their approach may be muffled by highway noise. After the stop, continue east on Highway 129.
4.3 mi (6.9 km)	Intersection of Highway 129 and Highway 101 and Searles Road. End of field trip.

Stop A (rolling stop)—San Andreas Fault Along Anzar Road

Stop highlights: Fault scarp along the San Andreas Fault, bedrock and vegetation contrasts, sag ponds

Anzar Road follows the San Andreas Rift Valley and provides views of some exceptional geomorphic features. The granitic basement rock exposed on the west side of the rift valley forms a steep escarpment covered with mixed oak and evergreen forests. Late Tertiary and Quaternary sediments on the east side of the fault are covered in grasslands. Sag ponds are common along this quiet rural road; Anzar Lake near the northeast end of the valley is particularly impressive. West of Anzar Lake the road ascends out of the rift valley through a scenic eucalyptus forest. There are no parking spaces along

Figure 2-14. Anzar Lake is a large sag pond in the San Andreas Rift Valley along Anzar Road.

this road, but ample visibility along the straight valley and the general lack of rural traffic shouldn't make stopping a concern for a picture break.

Stop B—Aromas Quarry

Stop highlights: Salinian basement complex, granodiorite, the Logan Gabbro, active granite quarry operations

The Aromas "Granite" Quarry area is a popular destination for field trips. Advanced access arrangements, hard hats, and boots are required to tour the quarry (access is forbidden during blasting and heavy mining activity). There is no true granite being mined in the quarry. The Jurassic-age rock consists of coarse crystalline gabbro and diorite (crystals of light-colored plagioclase feldspar and dark-colored clinopyroxene, hornblende, and amphibole give the rock a "salt and pepper" texture). Veins of some granodiorite and granitoid rock are also present. (The older Logan Quarry is just over the hill and is known for its gabbro; the local outcrop belt of this crystalline bedrock is called the Logan Gabbro). The rock is blasted, crushed, and sorted for use as aggregate and can be found at construction sites and rail lines throughout the region. A thin cover of Pliocene marine fossil-bearing sediments can be seen unconformably overlying the high walls of the quarry.

The Logan Gabbro has been correlated with equivalent exposures of gabbroic rocks at Gold Hill (south of Parkfield) and Eagles Rest Peak in the Tehachapi Mountains in Southern California—an offset distance of about 200 miles (320 km) along the San Andreas Fault.

Stop C—The San Andreas Fault at Pajaro Gap and Chittenden Bridge

Stop highlights: San Andreas Fault, bedrock and vegetation contrasts, Santa Cruz Mudstone, riparian habitat, springs

Figure 2-15. The main active pit at the Aromas "Granite" Quarry. On the basis of mineral composition, the quarry actually yields granodiorite and gabbro but no true granite at all. However, the rocks do have a granitic texture and appearance.

Please note: This stop is not recommended for groups of more than a few people because of the dangerous traffic on the road. Groups should proceed to "Stop C (continued)" described below for a safer and more casual examination of the area. However, if you do stop please pull off to the right beyond the guard rail, and pull ahead as far as possible to leave ample room and time for northbound drivers to see cars parked alongside the highway. Please note that as on all roadside stops, group leaders or individuals standing along this busy highway could be cited if proper precaution is not taken to ensure public safety.

Pajaro Gap is the narrow river passage between the southern Santa Clara Valley and the Monterey-Santa Cruz coastal plain region. The passage defines the southern end of the Santa Cruz Mountains. The Gavilan Range is to the south and east. The Pajaro River is usually a small spring-fed stream except during infrequent winter floods. Most of its headwater tributaries have been modified or diverted to support agricultural activities, groundwater recharge, municipal uses, and flood control. The river is the main drainage of the southern Santa Clara Valley and a large portion of the central Diablo Range. Its main tributary is the San Benito River that drains the San Andreas Rift Valley south of San Juan Bautista. West of the gap the river flows to Monterey Bay through the Pajaro Valley, the agricultural region around Watsonville.

Stop C (continued)

A small access road to the Crittenden Railroad Bridge is about 0.4 miles (0.7 km) north of where the San Andreas

Figure 2-16. The San Andreas Fault is poorly exposed crosses Highway 129. Landslides and plants have covered the fault zone (near the bend-in-road sign). The outcrop directly behind the car is weathered granitic rock; the outcrop on the right side of the image is sheared and weathered Miocene marine mudrocks (Santa Cruz Mudstone).

Figure 2-17. Beds of Santa Cruz Mudstone are gently dipping to the northeast towards Santa Clara Valley.

Fault crosses Highway 129. This is a much safer place to park and observe aspects of the landscape around Pajaro Gap. However, be cautious of broken glass and other material abandoned here. A good overlook view is next to the railroad bridge. (**WARNING! Do not walk on the rails or the bridge**; it is both unsafe and illegal. Trains can pass through this area at unexpected high speed, and their approach can be masked by highway noise.)

Figure 2-18. A drain pipe in the Santa Cruz Mudstone near the fault zone is a source of sulfur-rich water. Sulfur and mineral springs are common along faults throughout the region. Warning! Do not attempt to have field trip participants cross the road to examine the springs or outcrops. There isn’t enough room to stand next to the road. Rather, a single individual might carefully cross the road and fill a water jug. However, the rotten-egg smelling water is not safe to drink. Cattails grow in abundance near the springs.

Figure 2-19. Mount Pajaro is to the right (elevation 1,578 feet). A eucalyptus forest grows on the west side of the San Andreas Fault on the weathered granitic bedrock. Chaparral dominates the steep hillsides east of the fault where the soil is composed of weathered Tertiary sedimentary rocks. A riparian forest community dominates the narrow floodplain of the Pajaro River.

The trace of the San Andreas Fault is revealed on the hillside above Pajaro Gap by both a change in vegetation and a change in slope. Older “granite” quarry operations are visible on the east side of the river south of the railroad bridge. An outcrop of Santa Cruz Mudstone next to the bridge parking area is a much safer place to examine the rock than along the highway.

Figure 2-20. The original railroad bridge over the Pajaro River was heavily damaged by the 1906 earthquake. The bridge straddles a strand of the San Andreas Fault, which caused minor rotational offset of the bridge during the 1906 earthquake. The area also experienced heavy shaking during the 1989 Loma Prieta earthquake. Piles of gravel from the Logan Quarry are in the distance.

Selected References

City of San Juan Bautista, 2005, San Juan Bautista, the City of History [http://www.san-juan-bautista.ca.us/].

Harden, D., Stenner, H.M., and Blatz, I., 2001, The Calaveras and San Andreas Faults in and around Hollister, *in* Stoffer, P.W. and Gordon, L. Geology and natural history of the San Francisco Bay Area—a field-trip guidebook: U.S. Geological Survey Bulletin 2188, p. 145-154 http://geopubs.wr.usgs.gov/bulletin/b2188/].

Kelson, K.I., Baldwin, J.N., and Randolph, C.E., 2004, Paleoseismic assessment of the central Calaveras Fault, Southern Santa Clara County, California: U.S. Geological Survey External Research Award no. 1434-HQ-97-g-03151 [http://erp-web.er.usgs.gov/reports/annsum/vol39/nc/g3151.htm].

McLaughlin, R.J., Sliter, W.V., Sorg, D.H., Russell, P.C., Sarna-Wojcicki, A.M., 1996, Large-scale right-slip displacement on the East San Francisco Bay region fault system, California; implications for location of late Miocene to Pliocene Pacific Plate boundary: Tectonics, v. 15, no. 1, p.1-18.

Wagner, D.L., Green, H.G., Sausedo, G.J., and Pridmore, C.L., 2002, Geologic map of the Monterey 30' x 60' Quadrangle and adjacent areas, California: California Geological Survey, 1 sheet, scale 1:100,000.

3. Field Trip to Lexington Reservoir and Loma Prieta Peak Area in the Southern Santa Cruz Mountains

Trip Highlights: San Andreas Rift Valley, Quaternary faults, landslide deposits, Franciscan Complex, serpentinite, stream terrace deposits, Lomitas Fault, Sargent Fault, Cretaceous fossils, deep-sea fan deposits, conglomerate

This field trip examines faults, landslides, rocks, and geologic features in the vicinity of the San Andreas Fault and other faults in the central Santa Cruz Mountains in the vicinity of both Lexington Reservoir and Loma Prieta Peak (fig. 3-1). The field trip begins at Lexington Reservoir Dam at the boat dock parking area. To get to Lexington Reservoir Dam, take Highway 17 south (toward Santa Cruz). Highway 17 enters Los Gatos Creek Canyon about 3 miles (5 km) south of the intersection of highways 85 and 17. Exit at Bear Creek Road located about 5 miles (8 km) south of Highway 85. Cross the overpass and turn left back onto Highway 17 going north. Stay in the right lane and exit onto Alma Bridge Road. Follow Alma Bridge Road across Lexington Reservoir Dam and turn right into the boat dock parking area about 0.6 mile (1 km) from the exit on Highway 17 north. A Santa Clara County Parks day-use parking pass is required to park in the paved lot. The park day use pass is $5. Vehicles can be left here for the day to allow car pooling (the park is patrolled, but as always, take valuables with you).

Detailed geologic maps, cross sections, and descriptions featuring bedrock geology, faults, and landslide information useful for this field-trip area are available on-line at the *USGS San Francisco Bay Region Geology* website [http://sfgeo.wr.usgs.gov/]. McLaughlin and others (2001) have produced geologic maps of the Los Gatos, Laurel, and Loma Prieta 7.5 minute quadrangles that encompass this area. These maps are also consolidated within a research volume on the 1989 Loma

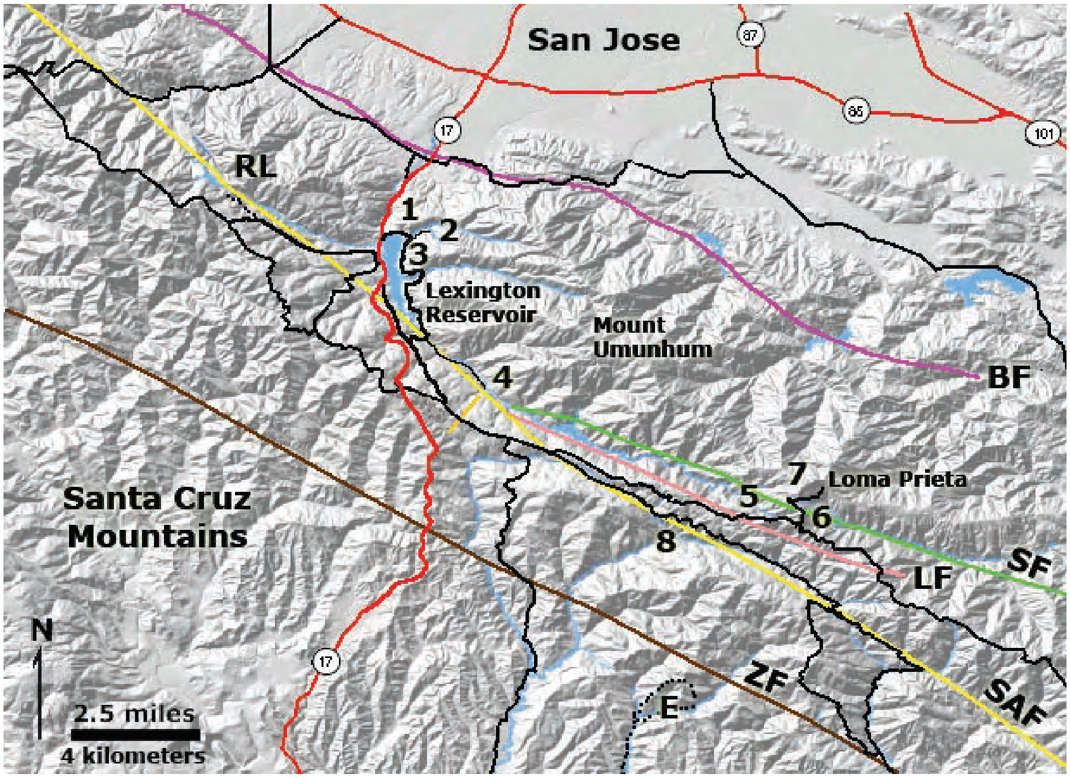


Figure 3-1. Map of the Santa Cruz Mountains between San Jose and Santa Cruz. Numbered stops (1-8) are part of this field trip. Faults shown in colors include the San Andreas Fault (SAF), the Lomitas Fault (LF), the Sargent Fault (SF), the Berrocal Fault (BF), and the Zayente Fault (ZF). Wrights Tunnel is shown in orange (at Stop 4). This map also shows other field-trip options in the vicinity that involve hiking. These include the Big Slump Trail to the epicenter of the 1989 Loma Prieta Earthquake in the Forest of Nisene Marks State Park (E) and a trail to Lake Ranch Reservoir (RL) in Sanborn County Park. The location of Wrights Tunnel is shown in orange at Stop 4.

Prieta earthquake edited by Wells (2004). Wentworth and others (1998) is a regional geologic map of the San Jose 30' x 60' quadrangle, and Brabb and others (1997) is a map of Santa Cruz County (see the reference list below).

The Santa Cruz Mountains segment of the San Andreas Fault extends from the San Juan Bautista area northward to Black Mountain. To the south of San Juan Bautista is a creeping segment that extends southward to the Parkfield area in central California. North of Black Mountain is the Peninsula segment that has remained essentially locked since the 1906 earthquake. The Santa Cruz Mountains segment, which experienced between 3 to 6 feet (1 to 2 m) of offset during the 1906 earthquake, was the locus of nearly a dozen magnitude 4-to-5-range earthquakes in the two decades preceding the magnitude 6.9 1989 Loma Prieta earthquake. These earthquakes occurred on the main trace of the San Andreas Fault and on other local faults that splay from the main trace.

Bedrock to the northeast of the San Andreas Fault in this region includes massive slivers or blocks of complexly faulted and folded terranes of the Franciscan Complex and Great Valley Complex. The Sierra Azul Block is an about 2.5 mile (4 to 5 km) wide belt of Great Valley Sequence (Mesozoic and early Tertiary sedimentary rocks) wedged between the San Andreas Fault and a system of ancient faults that roughly parallel the eastern side of the crest of the Sierra Azul Ridge. The northern extent of the Sierra Azul Block is near Wrights Tunnel south of Lexington Reservoir. The New Almaden Block is on the east side of the Sierra Azul Block and consists of Mesozoic age Franciscan Complex (chert, mudrocks, limestone, and basaltic volcanic rocks) and Coast Range Ophiolite (Jurassic-age serpentinized ultramafic rocks) that crop out in a belt extending from Gilroy northward through the Los Gatos-Lexington Reservoir area. Serpentinite exposures at the summit of both Mount Umunhum and Loma Prieta are part of the New Almaden Block. The New Almaden Block is also host to the cinnabar-bearing silica-carbonate deposits and includes the historically largest mercury production district in North America.

Bedrock west of the San Andreas Fault is part of the Santa Cruz Block that consist of late Tertiary marine sedimentary rocks that overlie Salinian crystalline basement rocks (granitoid, diorite, and gabbro that intruded older Paleozoic and Mesozoic metamorphic rocks). These crystalline basement rocks are exposed to the south in the Watsonville-Aromas area and to the northwest on Ben Lomond Mountain.

Road Log From Lexington Reservoir Dam to the Loma Prieta Summit Area

Distance	Description
0.0 mi (0.0 km)	**Stop 1—Lexington Reservoir Dam boat dock parking area** (see description below). Restrooms are available here, albeit primitive. After the stop, turn right when you leave the parking area and continue south on Alma Bridge Road. **Reset your trip mileage odometer to zero** as you leave the boat dock parking area.
0.4 mi (0.6 km)	The entrance to Lexington Quarry is on the left. A large quarry in the Franciscan Complex exposed along the Limekiln Creek valley produces crushed sandstone for construction aggregate.
0.6 mi (1.0 km)	**Stop 2—The Limekiln Trail** (see description below). Parking for about 10 vehicles is available here at the trail head. After the stop, continue south on Alma Bridge Road.
1.6 mi (2.6 km)	**Stop 3—Douglas B. Miller Picnic Area** (see description below). This is both a field-trip stop and lunch stop. Restrooms are available, albeit primitive. After the stop, continue south on Alma Bridge Road.
2.4 mi (3.9 km)	Alma Bridge Road winds into and out of Soda Springs Creek Canyon. Soda Springs road intersects Alma Bridge Road on the left (east). This road winds upward to the summit of Mount Thayer (mostly private land). A significant fire burned much of the hillsides along the east side of Lexington Reservoir in 1985 and threatened or damaged homes in the hills. The mostly chaparral-covered hills were more forested before the fire. The new vegetation is now a significant fire hazard during the dry summer-fall fire season.
4.1 mi (6.6 km)	Intersection of Alma Bridge Road with Aldercroft Heights Road. Turn right (west) on Aldercroft Heights Road. The bridge over Los Gatos Creek is labeled Alma Bridge 1952. **Stop 4—Wrights Tunnel (Optional; see discussion below).** Wrights Tunnel is a historic railroad tunnel that is now abandoned and sealed shut. It was severely damaged by the 1906 earthquake. The tunnel entrance is accessible via a trail between Aldercroft Road and Wright Station Road (to the south) and is downstream of Austrian Dam/Lake Elsman in the upper Los Gatos Creek drainage. Field trips can have access to this area with permission from the San Jose Water Company. Be aware that there is an abundance of poison oak along the trails and near the tunnel. Small dams, dikes, and ruins associated with the old, abandoned train line and station can be seen in the forest and along the trails that follow Los Gatos Creek.
4.6 mi (7.4 km)	An outcrop of serpentinite is visible along the left side of the
4.7 mi (7.6 km)	Intersection of Aldercroft Heights Road with the Old Santa Cruz Highway, turn left (south).
5.2 mi (8.4 km)	Along this section of the Old Santa Cruz Highway the soil along the road cuts changes consistency, becoming increasingly sandy, and redwood groves thrive (regrowth of the older lumbered forest). The change in soil reflects the transition of bedrock, soil, and vegetation across the San Andreas Fault Zone. However, the trace of the fault in not apparent along the highway.

Continued.

6.4 mi (10.3 km)	Mountain Charlie Road is on the right. This is a remnant of an early trail that crossed the Santa Cruz Mountains in the late 18th century connecting Mission Santa Clara with Mission Santa Cruz (probably following existing Indian trails). The trail, and the road system that followed, utilized a low divide along the ridge crest called Patchen Pass. As mining, lumbering, and other regional commerce grew, the need for a road across the mountains led to the establishment of the Santa Cruz Turnpike Company which, in turn, awarded a road-building contract in 1858 to one of the early white settlers in the area, Mountain Charlie McKiernan. This road roughly ran parallel to the modern Highway 17 and still exists as part of Mountain Charlie Road, which intersects Summit Road east of Highway 17. The name Patchen comes from an original settlement located near the summit.
8.4 mi (13.5 km)	Intersection of Old Santa Cruz Highway and Summit Road. Turn left (east) onto Summit Road.
10.2 mi (16.4 km)	Walkway overpass crosses Summit Road at school. This area experience extensive damage to property as a result of numerous surface ruptures from the 1989 Loma Prieta earthquake. Most of the surface ruptures were a result of the gravitational collapse of the mountaintop area during the shaking caused by the earthquake. The combined effects of earthquake shaking and the gravitational pull-apart of the mountain are called ridge-top spreading. All of the visible damage has been repaired and is no longer obvious today. However, the surface rupture effects of the 1989 Loma Prieta earthquake are still visible in remote sections of the Forest of Nisene Marks State Park (see the field-trip discussion in chapter 4).
10.8 mi (17.4 km)	Old School Vineyards are on Right. Summit Road straddles the San Andreas Fault Zone for the next quarter mile, but landscape features do not make the transition apparent.
11.0 mi (17.7 km)	Summit Center Market is on the left. (Food and a restroom are available here.)
11.2 mi (18.0 km)	Soquel-San Jose Road is on the right. To the east of this intersection, Summit Road enters a straight wooded canyon of Laurel Creek that defines the rift valley of the San Andreas Fault. Look for geomorphic features along the road that reveal the trace of the fault.
12.2 mi (19.6 km)	Summit Road ascends into a flat area where a number of sag ponds can be seen along the right side of the road.
12.9 mi (20.8 km)	Intersection of Highland Way and Mount Bache Road. Continue strait onto Mount Bache Road. Highland Way descends into headwaters region of Soquel Creek, which drains a straight valley along the San Andreas Fault (see Stop 8 below). **Be cautious driving on Mount Bache Road**. Although the road is paved, it is windy, narrow, and uneven due to slumping in many places. Vehicles traveling downhill may have more difficulty stopping that those traveling uphill.
13.9 mi (22.4 km)	Mount Bache Road ends where Loma Prieta Avenue comes in from the left and continues uphill. Proceed straight onto Loma Prieta Avenue (continuing south).

Continued.

14.4 mi (23.2 km)	Outcrops of steeply dipping and contorted sandstone and shale beds start to appear in cuts along Loma Prieta Avenue (continuing uphill). These are discussed in stops 4 and 5.
16.2 mi (26.0 km)	**Stop 5—Loma Prieta Avenue** (see description below). A parking area is on the right surrounded by large boulders and a gate (do not block the gate—the steep dirt road is used for back country patrols by open space rangers). Additional pulloffs are ahead on either side of the road where Loma Prieta Avenue crosses a narrow divide between the headwaters canyon of Los Gatos Creek on the left (north) and Soquel Creek in the San Andreas Rift Valley on the right (south). After the stop, continue south on Loma Prieta Avenue. The pavement eventually ends, but the graded road is maintained and is suitable for any passenger vehicle.
17.1 mi (27.5 km)	**Stop 6—Intersection of Loma Prieta Avenue with Mount Madonna-Summit Road.** A road to Loma Prieta Peak area is on the left. (See description below.) After the stop, turn left on the road leading to Loma Prieta Peak. (The no-trespassing sign is not enforced in this lower section of the road, however farther along the road gates indicate where private property begins). The road is rough, but is passable up to a large dirt parking area near the intersection of three private roads.
17.3 mi (27.8 km)	Along the route uphill toward Loma Prieta Peak, roadside outcrops of interbedded Late Cretaceous sandstone and shale give way to conglomerate. This, in turn, gives way to exposures of serpentinite of Jurassic age. This transition marks the location of the fault zone of the Sargent Fault (also visible at Stop 7). Intermittent views of the southern Santa Clara Valley are on the right.
17.5 mi (28.2 km)	**Stop 7—Loma Prieta summit parking area** (see description below). A relatively large parking area is located on the left near the intersection of a gated road to Loma Prieta Peak and another unpaved road that leads downhill toward private residences built on the east side of Loma Prieta Peak. A third road (with a gate) leads north along the ridgeline of Sierra Azul ridge. Do not attempt to procede into these areas without permission. After the stop, return down Loma Prieta Avenue to Mt. Bache Road.
23.0 mi (km)	At the Intersection of Mount Bache Road and Highland Way turn left (south). Highland Way descends into the upper valley of Soquel Creek that is also the rift valley of the San Andreas Fault. Highland Way is a road destined for trouble—for much of the next 6 miles the road crosses Quaternary landslide deposits. The rugged condition of sections of the road suggests that parts of the landslide complex are still actively moving. The San Andreas Fault follows the west side of the valley near creek level but buried beneath landslide deposits.
26.0 mi (41.8 km)	**Stop 8—Landslide on Highland Way** (see description below).
26.3 mi (42.3 km)	**End of field trip.** A trail head for the Soquel Demonstration Forest and the Forest of Nisene Marks is on the right (farther south) along Highland Way. Parking is available here for paths that lead to the epicenter area for the Loma Prieta earthquake of 1989. Turn around here and return to Highway 17 using Summit Road. Alternatively, continue south along Highland Way and Buzzard Lagoon Road to get to Santa Cruz-Watsonville area and to Highway 1.

Stop 1—Lexington Reservoir Dam Boat Dock Parking Area

Stop highlights: View of the San Andreas Fault Rift Valley, a range-front thrust fault, Franciscan Complex, graywacke

Lexington Reservoir Dam is located about 1.5 miles (2.4 km) above the mouth of Los Gatos Creek Canyon (at the town of Los Gatos). The dam was renamed the James J. Lenihan Dam in 1997 to honor a former director of the Santa Clara Valley Water District. Two small communities, Lexington and Alma, existed in the upper, broad valley of Los Gatos Creek before the reservoir was constructed. The dam and reservoir were completed in 1952. The dam was built for flood control and to moderate the flow of water to Vasona Reservoir and ground-water-recharge percolation ponds farther downstream in the Campbell area.

Below the dam, Los Gatos Creek Canyon separates El Sereno (the mountain on the west side of the canyon) and St. Joseph's Hill (to the east; it is part of the Sierra Azul Open Space Preserve). A trail system between Los Gatos and the reservoir traverses the canyon and the eastern hillsides. Rocks exposed in the canyon and along the trails include sandstone, conglomerate, chert, basaltic volcanic rocks, and serpentinite and greenstone. The rocks are fragmented into car- to building-sized blocks and mixed together. Where these materials are too small to be differentiated into map units they are collectively assigned to a unit called a *mélange* (meaning mix of rocks). In some areas, belts of similar rock types can be mapped over many miles. The large blocks are bounded by faults that predate or are concurrent with the local development of the San Andreas Fault system in late Tertiary time. One large block of sandstone and mudrock of Cretaceous age is partially exposed in the cut across the road and in the hillsides below the boat-dock parking area.

The view to the southwest across Lexington Reservoir reveals the trace of San Andreas Fault (fig. 3-2). It forms a side-hill bench (a break in the slope) across the hillside on Castle Rock Ridge in the distance. Conifers grow on the uphill, steeper slope on the west side of the fault. The trace of the fault continues north into Lyndon Canyon that separates El Sereno Ridge (on the right) and Castle Rock Ridge (on the left). To the south, the trace of the San Andreas Fault follows upper Los Gatos Creek before ascending over the ridge along Summit Road along the crest of the Santa Cruz Mountains.

In this region of the Santa Cruz Mountains, the rocks east of the San Andreas Fault consist of three groups—the Coast Range Ophiolite, the Franciscan Complex, and the Great Valley Sequence. The Coast Range Ophiolite is comprised of rocks that formed in the ocean's crust during the Jurassic and Cretaceous periods. These rocks have traveled great distances from their place of origin and consist mostly of serpentinized ultramafic rocks and greenstone. The Franciscan Complex contains of a mix of oceanic sedimentary and volcanic rocks of Jurassic to Cretaceous age; this rock assemblage includes pillowed basaltic volcanic rocks, radiolarian chert, mudrocks, sandstone, limestone, and conglomerate. The basalts represent lava flows that probably formed at or near a mid-ocean ridge. These were overlain by open-ocean and continental margin sediments before being accreted onto the edge of the continent through plate-tectonic motion. The Great Valley Sequence consists mostly of sandstone and shale of Cretaceous age deposited in a fore-arc basin developed between an Andean-style volcanic arc and the associated subduction zone to the west. Younger marine sedimentary formations (including the Temblor Sandstone and Monterey Formation of Miocene Age) occur in the Cupertino basin, a great sediment-filled crustal downwarp located beneath the alluvial plain extending eastward from the foothills in the Los Gatos and Saratoga region and extending to San Jose and southern San Francisco Bay.

Rocks on the Santa Cruz (west) side of the San Andreas Fault are part of the Santa Cruz Block, an expansive geologic terrane that consists mostly of sedimentary rocks overlying older Salinian crystalline basement rocks. In the headwaters region of Los Gatos Creek, these rocks consist entirely of marine sedimentary rocks of early Tertiary age (Butano Sandstone of Eocene age and San Lorenzo and Vaqueros Formation mostly of Oligocene age).

In this region, rocks younger than the San Andreas Fault include the Santa Clara Formation of Pliocene to Quaternary age. The Santa Clara Formation consists of stream cobbles, gravel, sandstone, siltstone, and mudstone, and bears freshwater gastropods, pelecypods, and terrestrial plant and vertebrate fossils that are about 3.6 to 0.4 million years old. Younger terrace gravels along stream valleys incorporate a mix of all the above rock-types mentioned.

A walk down to the shore near the boat dock provides a view of Franciscan rocks (to the east) thrust-faulted over steeply dipping gravels of the Quaternary Santa Clara Formation (to the west). The faulted contact is also visible on the far side of the bay of Limekiln Creek: however the outcrop area may not be exposed at high water levels. The thrust fault is part of the Lexington Fault Zone that runs roughly parallel to the mountain front along the east side of the reservoir. The fault system extends from the park's boat dock parking area southward to where it merges with the San Andreas Fault in the vicinity of Wrights Tunnel (see below). Uplift along the thrust fault and other faults are responsible for the high, rugged topography of the Sierra Azul uplands (for geologic maps and additional information, see McLaughlin and others, 2000). Likewise, the broad valley flooded by Lexington Reservoir may be partly due to tectonic downwarping in addition to the erosional downcutting by Los Gatos Creek.

Stop 2—The Limekiln Trail

Stop highlights: An active slump, a fault, serpentinite, sepentinite soil, vegetation contrasts, graywacke and other rocks

The Limekiln Trail climbs to the summit area of El Sombroso, a high point at the north end of the Sierra Azul Ridge. The destination of this stop is a landslide about 0.25 mile

Figure 3-2. Northwest view from the boat-dock parking area showing Lexington Dam and the location of the San Andreas Fault trace (SAF) on the distant hillside west of Highway 17. The fault trace follows a side-hill bench below the upper steep slopes of Castle Rock Ridge on the horizon. The fault continues northward into the valley of Lyndon Canyon.

(0.4 km) uphill from the trail head (fig. 3-3). The trail climbs a moderate grade before leveling out near the slide area. Do not go on the trail if the park police have closed it (park patrol officers will issue tickets).

The lower part of the trail ascends past outcrops of metabasalt, and sandstone and mudrock (also called graywacke) similar to rocks at Stop 1. The landslide occurs along the east side of a fault separating bedrock consisting of sandstone bedrock and serpentinite. The slump provides an excellent observatory of landslide processes, weathering of serpentinite, stream erosion, and vegetation characteristics associated with serpentinite and sandstone bedrock terranes. Phacoids (lenticular-shaped cobbles and blocks) of serpentinite have accumulated in the stream at the toe of the landslide. Many of these phacoids display grooves, gashes, and a smooth surface polish created by grinding and shearing action within the landslide or within a fault zone before being exposed and transported by erosion. The stream also yields boulders of chert, slate, and rounded stream cobbles derived from sources higher on the mountainside.

A belt of barren, gray limestone outcrops is visible on the upper hillsides across Limekiln Creek valley. In addition, groves of manzanita reveal the presence of serpentinite bedrock along the skyline across the valley. Approximately a mile south of the landslide on the opposite side of the valley is the Lexington Quarry, a large active quarry where rock (mostly metasandstone) is mined and processed into aggregate for construction. Geologic maps of the area show a system of southeast-trending faults through the area. One large fault mapped in this area, the Limekiln Fault, basically follows the trace of the stream valley. The fault exposed along the side of the landslide is only a part of the larger fault system. Be sure to examine outcrops in the creek to the right of the landslide. Note shearing features in the faulted bedrock, and observe the chaotic character of debris-flow deposits along the stream banks.

Figure 3-3. An active landslide along the Limekiln Trail causes trail closure during wet seasons. In recent winters the road has been offset by several feet. During dry months the slide area is relatively safe to examine but be aware that rocks and soil in steep slopes may be unstable from recent movement. The landslide formed in deeply weathered serpentinite, but fresh blocks of rock material have accumulated in the stream at the toe of the slump.

Stop 3—Douglas B. Miller Picnic Area

Stop highlights: An unconformity between weathered Quaternary gravels and Franciscan Complex sandstone

The Miller Point Picnic Area is located on a small peninsula in Lexington Reservoir. Besides being an excellent place for a picnic, the park offers an opportunity to examine rocks exposed along the reservoir shoreline. Large blocks of graywacke sandstone stand out on the shore (during low water). Wave erosion at the high water line has exposed an ancient stream terrace deposit consisting of a mix of gravel derived from upland localities (fig. 3-4). At some places along the shore it is possible to see the gravel resting unconformably on an eroded surface of the older graywacke bedrock. The gravel was deposited along the ancestral Los Gatos Creek. The stream has carved about 65 feet (20 m) deeper into the valley since the time the terrace deposits were formed.

The terrace gravel contains an assortment of different rock types, with sandstone being the most abundant. Rock types at the picnic area but not found at the Limekiln Trail stop (above) include conglomerate and volcanic cobbles (clasts derived from the conglomerate) (fig. 3-5). The volcanic clasts are dominantly andesite and possibly dacite—these volcanic rocks are intermediate in composition between more felsic rock (rhyolite) and mafic rock (basalt). The volcanic cobbles display an abundance of phenocrysts (visible crystal mineral grains) surrounded by a finer ground mass. Some of the cobbles may be the intrusive igneous equivalent, granodiorite, which has the same mineral composition of its volcanic form, andesite. Some of the clasts contain xenoliths (pieces of the original host rock that was intruded by the volcanic material). The occurrences of these clasts in the terrace gravels demonstrate how earth materials are recycled (formed, eroded, deposited, exposed, eroded, and deposited again).

The volcanic cobbles are derived from outcrops of Cretaceous-age conglomerate throughout the upper hillsides of the Sierra Azul. It also forms part of the resistant ridge crest on the southwest side of Mount Umunhum and along the ridge south of Loma Prieta Peak and probably elsewhere under the forest cover. Similar gravel deposits can be found around the parking area at Los Trancos, nearly 14 miles (20 km) to the northwest. The offset of these gravels by the San Andreas Fault helps to determine the rate of slip along the fault over time.

Many of the volcanic clasts in the terrace deposit are rotten—they practically crumble in your hands (fig. 3-5). This is a result of chemical weathering of the rocks in the shallow surface environment (processes associated with soil development). The relationship between deposition of the terrace gravels and the motion along faults affecting stream drainages is unclear. However, the occurrence of terrace deposits in upland valleys elsewhere in the Santa Cruz Mountains and in the region is related to erosional valley-broadening periods during the Pleistocene. This is opposed to valley-deepening periods when streams carve downward into their flood plains. During times of high-standing sea level (during interglacial periods), the rise in stream base level tends to allow streams to backfill their channels with sediment. During wetter periods in the West (associated with glaciation), the combined influence of increased stream flow, reduction in sediment supply (due to increased vegetation), and lowered sea level (due to the formation of continental glaciers) induces streams to carve into their flood plains. Incising streams locally leave bench-like, gravel-covered terraces along the valley sides.

Stop 4—Wrights Tunnel

Stop Highlights: A historic railroad tunnel built through the San Andreas Fault Zone

Wrights Tunnel (fig. 3-6) was constructed by the Southern Pacific Railroad over (and through) the Santa Cruz Mountains. The tunnel took 3 years to build. During construction in 1879, Chinese laborers excavating the tunnel encountered a source of natural gas that exploded and burned, killing 31 people. The completed tunnel was 6,000 feet long and ran between two historic mountain communities (Wrights Station on the east and Laurel on the west). The tunnel passes beneath Summit Road east of Highway 17. The primary income of the railroad was from tourism between the Bay Area and resorts and recreation in Santa Cruz. The peak in use of the train line through

Figure 3-4. Stream boulders and gravel of Quaternary-age deposits overlie Cretaceous-age sandstone bedrock along the shore of Lexington Reservoir at Miller Point Picnic Area.

Figure 3-5. A rotten (partial weathered) cobble a mafic volcanic porphyry has an inclusion of gray metasandstone. This cobble was probably derived from the Late Cretaceous-age conglomerate found on Mount Umunhum and Loma Prieta peaks. That conglomerate originally accumulated in the ocean, possibly at the mouth of a deep-ocean canyon offshore of what is today southern California or Mexico. The sediments were consolidated into conglomerate before being transported northward by plate tectonic motion along the San Andreas Fault and fault systems that predate the San Andreas Fault. Similar blocks of conglomerate bearing clasts of mafic volcanic porphyry occur in gravels of the Corte Madera facies of the Santa Clara Formation exposed at the Monte Bello and Los Trancos Preserves nearly 15 miles (25 km) to the north along Skyline Ridge. The measurable offset of the Corte Madera facies provides information about the timing and rate of movement along the San Andreas Fault.

Figure 3-6. View looking out of the west end of Wrights Tunnel toward Los Gatos Creek. The tunnel is now full of leaking cracks that are feeding a small stream flowing from the mouth of the passage.

the Santa Cruz Mountains was in the 1910s and 1920s, before fading as improvements were made to the highway system through the mountains that provided access to the coast by automobile. The tunnel was dynamited shut in 1942 by the U.S. Army out of fear that it might be used by a Japanese invasion force.

Wrights Tunnel was damaged by the 1906 earthquake (fig. 3-7). The fault rupture offset the tunnel about 400 feet inside the Wrights Station entrance. It took 2 years to rebuild the tunnel. Between 3.5 and 5 feet (1 to 2 m) of right-lateral offset were reported on a strand of the San Andreas Fault in the tunnel (Prentice and Schwartz, 1991); however, analysis of historical documents show that the tunnel was offset a total of at least 5.6-5.9 feet (1.7-1.8 m) (Prentice and Ponti, 1997); the main trace of the San Andreas Fault has been mapped east of the trail entrance (McLaughlin and others, 2001). Some early reports suggest as much as 4 feet (1.2 m) of vertical offset may have occurred. However, modern re-evaluation suggests that the fault zone is about 0.25 mile wide and that a total of 6 feet (2 m) of offset occurred in the vicinity of Wrights Tunnel. The geologic map of Los Gatos quadrangle (USGS Miscellaneous Field Investigation Map 2373) shows that the main trace of the San Andreas Fault is inferred to cross Los Gatos Creek several hundred feet northeast of the east tunnel entrance. Most of the mapped cracks that were recorded from the 1989 Loma Prieta earthquake occurred outside of the zone of faulting that occurred in 1906 in Wrights Tunnel.

Figure 3-7. Damage to the railroad track between Wrights Station (near the tunnel) and Alma caused by the 1906 earthquake. Both historic settlements and the rail line no longer exist. The gravel road now follows the rail path. The photograph is from an unspecified source reproduced by Iacopi (1969).

Please note that there is limited parking and trail access to Wrights Tunnel, and poison ivy is abundant everywhere. The tunnel is closed, and permission for group access to the area is required from the San Jose Water Company.

Stop 5—Loma Prieta Avenue

Stop highlights: Views of the San Andreas Rift Valley and Monterey Bay, Cretaceous fossils, conglomerate, turbidites

A parking area is on the right surrounded by large boulders and a gate (do not block the gate—the steep dirt road is used for backcountry patrols by open space rangers). Additional pulloffs are ahead on either side of the road where Loma Prieta Avenue crosses a narrow divide between the headwaters canyon of Los Gatos Creek on the left (north) and Soquel Creek Canyon in the San Andreas Rift Valley on the right (south). This stop involves a short walk along Loma Prieta Avenue to examine roadside outcrops and the regional landscape. Loma Prieta Peak (covered with radio antennas) is visible on the north side of the road across the headwaters valley of Los Gatos Creek.

On the south side of the road the slope descends steeply into the linear valley of the headwaters region of Soquel Creek (fig. 3-8). The linear character of Soquel Creek canyon reflects the location of the San Andreas Fault. The forested ridge on the opposite side of the canyon is part of the Forest of Nisene Marks (the location of the epicenter of the 1989 Loma Prieta earthquake). The more distant views along the saddle area include a sweeping view to the south toward Monterey Bay and Monterey Peninsula and the Santa Cruz urban coastal corridor.

Other than a few scattered homes and some radio towers, the upland area around Loma Prieta Peak is relatively wild country. The isolated country is prime mountain lion habitat. The west- and south-facing slopes tend to have chaparral to mixed shrub-deciduous forest (particularly bay laurel), whereas the wetter, cooler north- and east-facing slopes are forested with mixed evergreen (spruce-pine-redwoods). However, the character of the bedrock and derivative soil plays an important role in supporting different types of vegetation. Loma Prieta receives the greatest amount of rainfall annually in the South Bay region—on average, mixed precipitation is equivalent to about 60 inches of rainfall.

Figure 3-8. View looking south at the Loma Prieta Road (LPA) saddle area. The rift valley of the San Andreas Fault (SAF) is developed in the headwaters of Soquel Creek (which flows to the right). To the south of a divide in the rift valley is Corralitos Creek that flows south into the Watsonville area (W). A linear ridge and a change in vegetation mark the location of the Lomitas Fault (LF). Seen in the distance are Monterey Bay (MB), and the Santa Lucia Range (SLR), which at the northern end becomes the Monterey Peninsula.

Vegetation and topography reveal the trace of the Lomitas Fault along the hillside about 600 feet (200 m) below the south side of the road (fig 3-9). On the north side of the road, the Sargent Fault follows the valley of Los Gatos Creek (see Stop 6 discussion). Both faults merge with the San Andreas Fault in the area between Wrights Tunnel and Austrian Dam in the upper Los Gatos Creek canyon.

Figure 3-9. Vegetation changes and topography reveal the trace of Lomitas Fault (LF) below the saddle area along Loma Prieta Avenue. Raised relief on the south side of the fault suggests that the Loma Prieta Peak side of the fault dropped relative to the opposite side. However, the fault probably shares the right-lateral motion of the San Andreas Fault and other faults in the region. The valley of Soquel Creek is on the upper right. The stream drains into the ocean in the Capitola neighborhood of Santa Cruz.

Road cuts along Loma Prieta Avenue expose Late Cretaceous age marine sedimentary rocks. The alternating sandstone and shale beds are called turbidites. Turbidites form from sediment-bearing underwater landslides (turbidity currents) that roll down the Continental Slope and spread out on the deep ocean floor. The heavier sand is deposited first (forming sandstone) and the finer silt and clay settle out later (forming mudstone and shale). Turbidites are characterized by graded bedding, moderate sorting, and well-developed primary structures (including traces that reveal current orientation, bedding lamination, and bioturbation features from organisms that fed or lived in the sediment). These deep ocean sediments are now exposed in many areas throughout the Santa Cruz Mountains. The turbidite sandstone and mudstone cut by the construction of Loma Prieta Avenue near the parking area display exceptional examples of spheroidal weathering (the early stages of chemical weathering of freshly fractured rock).

In the middle of the saddle area are outcrops bearing massive sandstone, conglomerate, and fossiliferous marl (bearing oysters, corals, calcisponges, and other invertebrates and trace fossils) (figs. 3-10 and 3-11). The conglomerate bears mafic-mineral bearing volcanic clasts (andesite and dacite) in a fine sandy matrix. These conglomerate beds are likely the source of the deposits seen at the Miller Point Picnic Area (Stop 3). The occurrence of the oyster-bearing beds is unusual. Modern oysters live in brackish, shallow-water environments just as they probably did in Cretaceous time. How this deposit arrived at its location amongst deep-water deposits can only be speculated (perhaps carried down slope as a great submarine landslide after an earthquake, massive storm, or giant tsunami impacted the coast). Elder (1991) provides more information about the paleontology of this site.

Stop 6—Intersection of Loma Prieta Avenue with Mount Madonna-Summit Road

Stop highlights: Cretaceous turbidites, conglomerate, views of the southern Santa Cruz Mountains region

A parking area near the intersection of Loma Prieta Avenue and Mount Madonna-Summit Road is the best place to examine the turbidite beds (alternating sandstone and shale layers). An optional walk (or drive) is to continue along Mount Madonna-Summit Road to examine folds in the sandstone and shale and conglomerate (fig. 3-12). A view of the straight valley of Uvas Creek Canyon and the more distant Santa Clara Valley in the vicinity of Morgan Hill (near El Toro Peak) is approximate 0.2 miles south of the intersection. **Warning: Be cautious of traffic while walking, especially near blind bends in the road.**

Stop 7—Loma Prieta Summit Area

Stop highlights: Views of the Sargent Fault Zone, Sierra Azul Ridge, Mount Umunhum, serpentinite

Figure 3-10. A layer of conglomerate between beds of sandstone. The largest clasts of volcanic rock and sandstone are at the base of the graded bed, suggesting that rock hammer handle is in the direction of the top of the unit. Much more massive beds of conglomerate occur throughout the area along Loma Prieta Avenue and Mount Madonna Summit Road. Conglomerate beds also occur in the western Mount Umunhum summit area.

Figure 3-12. This road cut along Mount Madonna-Summit Road displays sandstone and shale beds (turbidites) and conglomerate cross cut by folds and minor fault offset.

Stop 7 is along the road to the Loma Prieta Peak summit area (fig. 3-13). An old sign near the intersection of Loma Prieta Avenue and Mount Madonna-Summit Road warns travelers to “keep out.” However, the road is passable to the intersection of three gated roads farther along the route. Proceed up the road for 0.6 miles to a large circular parking area. Along the way, pay attention to the scenery and bedrock changes in the road cuts. Drivers should pay attention for potholes, but the road is passable for any vehicle. Unfortunately, much of the summit area of Loma Prieta and the passage along Sierra Azul Ridge to Mount Umunhum are closed to the public, although field trips have been granted permission to enter in the past.

Along the route, the road crosses the Sargent Fault (fig. 3-14). The fault is indicated by the transition from conglomerate, sandstone, and shale (turbidites) to serpentinite, as is visible in roadside outcrops. Small pull outs along the route provide scenic vistas to the south and east of the Santa Clara Valley and the foothill country and canyons east of the crest of the Santa Cruz Mountains. The Sargent Fault is considered an earthquake fault—showing active recent seismicity and having

Figure 3-11. Small oysters and calcisponges in a fine mudrock groundmass occur in an outcrop area near the center of the saddle area along Loma Prieta Avenue. Like the conglomerate beds, the oyster shells and other fossil material were probably deposited in a submarine-fan channel far offshore (in a setting perhaps similar to the bottom of submarine Monterey Canyon today). Today, oysters thrive in brackish estuary and nearshore waters but cannot tolerate predation or environmental conditions typical of open-ocean marine waters. These fossil oysters probably lived in a similar habitat.

Figure 3-13. Serpentinite forms the core of Loma Prieta Peak. The chaparral- and manzanita-covered mountain top is privately owned, and space is leased for radio towers. The area is closed to public access. This view is from along the road to Stop 7.

Figure 3-14. This view is looking south along the straight canyon of upper Uvas Creek from along the road to Stop 7. The valley follows the trace of the Sargent Fault southward to the Gilroy area and on to Hollister where it intersects the Calaveras Fault. Mount Madonna-Summit Road follows the ridge on the right.

association with damaging earthquakes in historic times in the Gilroy and Hollister region. The fault intersects the San Andreas Fault near Elsman Reservoir (upstream of Wrights Tunnel) and connects with the Calaveras Fault in the vicinity of Hollister. Like all major faults in the area, it displays evidence of right-lateral (dextral) offset. However, evidence of some vertical component offset is suggested by exposures of the fault scarp along the Los Gatos Creek Canyon. The west side of the fault (toward the creek) appears to be raised as much as 200 feet (60 m) relative to the Loma Prieta and Sierra Azul Ridge side of the fault. This perspective is best seen from near the Stop 7 parking area (fig. 3-15).

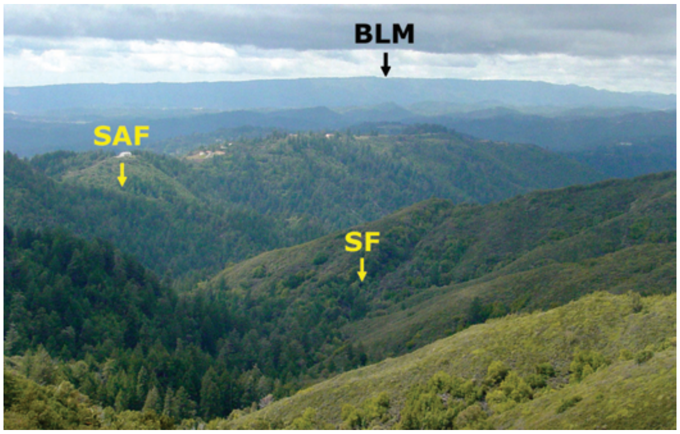


Figure 3-15. View looking west from the Stop 7 parking area. The linear scarp of the Sargent Fault (SF) is highlighted by a line of coniferous forest on its northwest-facing slope. The location where the trace of the San Andreas Fault (SAF) crosses the ridge along Summit Road is visible on the opposite side of Los Gatos Creek Canyon. Ben Lomond Mountain (BLM) is the long, gentle ridge on the western horizon.

Figure 3-16. View looking north toward Sierra Azul Ridge and Mount Umunhum. The low section along the ridge is underlain by early Tertiary carbonaceous shale and sandstone (containing land plant material). The higher section of the ridge consists of Cretaceous-age conglomerate. The eastern peak of Mount Umunhum (near the large cement-block-shaped structure of an abandoned military radar facility) consists of a complex mix of rocks, mostly serpentinite, associated with the Coast Range Ophiolite.

The Stop 7 parking area also provides an opportunity to view the crest of the Santa Cruz Mountains extending north to the Mount Umunhum summit area and beyond (fig. 3-16). It also is an excellent location to examine serpentinite outcrops (fig. 3-17).

Figure 3-17. This view shows part of a large serpentinite block near the Stop 6 parking area. The rock reveals aspects of how mantle rock is converted to serpentinite. Pink crystalline masses are relatively unaltered ultramafic rock (harzburgite and peridotite). These are surrounded by black serpentinized material (resulting in the loss of crystalline texture). The blue veins are asbestoid minerals (mostly crysotile) and magnesium hydroxide-rich minerals. Surficial weathering converts these minerals to magnesium-rich clay soil.

Stop 8—Landslide on Highland Way

Stop highlights: Landslides, Tertiary sandstone and shale, San Andreas Rift Valley

Along Highland Way, about 3 miles (5 km) west of the intersection of Summit Road, are a series of landslides that have frequently closed the road to through traffic. The road was most recently closed by massive landslides that occurred in January of 1997 with additional activity the following year (fig. 3-18). The road has since been repaired, but the fresh landslide escarpments are still visible (even after construction repairs have smoothed out the typically chaotic landscape of a slide area). The steep, forested landscape throughout this area displays abundant evidence of landslide activity—both active slides and other more ancient slides that are probably dormant. A combination of factors makes this area prone to landslides, including:

- long, steep slopes;
- bedrock consisting of sedimentary rock (mostly shale and highly fractured sandstone);
- a seasonally wet period;
- mountain climatic conditions that promote organic activity and associated weathering;
- rapidly down-cutting streams that undermine slopes;
- human activity—particularly their preponderance to cut slopes to build roads; and
- frequent landslide trigger mechanisms, including earth quakes and major storms.

Figure 3-18. The Highland Way landslide is part of an extensive landslide complex that extends along the east side of the San Andreas Rift Valley in the upper Soquel Creek watershed. Highland Way cuts across the landslide complex and has experienced many landslide-related problems, with the latest massive landslide taking place in January, 1997 which closed the road for several years. Extensive work was conducted to remove dead trees and loose rock before the road could be repaired. This looser material is derived from Tertiary rock which consists of dark, hard, siliceous marine shale with interbedded arkosic sandstone. This sequence of marine strata forms a belt along the eastern side of the San Andreas Rift Valley for many miles extending to the south from the Highland Way landslide area.

The bedrock exposed in the slide area is interbedded quartz-rich to arkosic sandstone, and shale of early Tertiary age (Eocene Mount Madonna Sandstone; deposited between 34 to 56 million years ago). On the west side of Soquel Creek valley the bedrock is a mudstone of late Tertiary age (Purisima Formation; of Pliocene age, about 3 million years). Marine fossils in the Purisima Formation demonstrate that the Santa Cruz Mountains have risen from below sea level to more than 3,000 feet (1 km) high in roughly 3 million years. In addition, another 10,000 to 13,000 feet (3 to 4 km) of rock has probably been eroded from the crest of the Santa Cruz Mountains in the past 5 million years (McLaughlin and others, 2001).

Many trees in the Soquel State Demonstration Forest (across the valley) were damaged or fell in the 1989 Loma Prieta earthquake. The magnitude 6.9 earthquake occurred on Tuesday, October 17, 1989, at 5:04 p.m. PDT. The epicenter of that quake was located at 37°02'N, 120°53'W, approximately 4 miles (6.5 km) south of the Highland Way slide area in the heart of the Forest of Nisene Marks State Park (see chapter 4). The depth of the main shock was approximately 11.5 miles (18.5 km) below the surface. The fault plane is not vertical, but rather, it dips steeply at a high angle toward the southwest (NcNutt and Toppozada, 1990). The earthquake produced little physical evidence of right-lateral offset on the surface, however the earthquake initiated numerous slope failures and slump-related ground ruptures throughout the Santa Cruz Mountains, particularly along the Summit Road corridor. Near the epicenter, uplift of about 22 inches (55 cm) resulted, whereas east of the fault subsidence occurred in the order of about 6 inches (15 cm) for the area around Loma Prieta peak. Within several miles distance from these areas, the measurable elevation offset diminishes to being negligible.

Selected References

Brabb, E.E., Graham, S., Wentworth, C., Knifong, D., Graymer, R., and Blissenbach, J., 1997, Geologic map of Santa Cruz County, California: U.S. Geological Survey Open-File Report 97-489, 1 sheet, scale 1:62,500 [http://pubs.usgs.gov/of/1997/of97-489/].

Elder, W.P., 1991, An unusual Late Cretaceous fauna from an oyster-rich interval in the Santa Cruz Mountains of California: U.S. Geological Survey Bulletin 1934-E, p. E1-E16.

Iacopi, Robert, 1964, Earthquake Country: Menlo Park, California: Lane Book Company, 191 p.

Lawson, A.C., chairman, 1908, The California earthquake of April 18, 1906—Report of the State Earthquake Investigation Commission: Carnegie Institution of Washington Publication 87, 2 vols.

McLaughlin, R.J., Langenheim, V.E., Schmidt, K.M., Jachens, R.C., Stanley, R.G., Jayco, A.S., McDougall, K.A., Tinsley, J.C., and Valin, Z.C., 2000, Neogene contraction between the San Andreas Fault and the Santa Clara Valley, San Francisco Bay region, California, *in* Ernst, W.G. and Coleman, R.G., eds., Tectonic Studies of Asia and the Pacific Rim: Geological Society of America, International Book Series, v. 3, p.265-294.

McLaughlin, R.J., Clark, J.C., Brabb, E.E., Helley, E.J., and Colon, C.J., 2001, Geologic maps and structure sections of the southwestern Santa Clara Valley and southern Santa Cruz Mountains, Santa Clara and Santa Cruz Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map 2373, 5 sheets, scale 1:24,000 [http://geopubs.wr.usgs.gov/map-mf/mf2373/].

McNutt, S.R., and Toppozada, T.R., 1990, Seismology of the 17 October 1989 earthquake: California Division of Mines and Geology Special Publication 104, p.11-27.

Prentice, C.S. and Schwartz, D.P, 1991, Re-evaluation of 1906 surface faulting, geomorphic expression, and seismic hazard along the San Andreas Fault in the southern Santa Cruz Mountains: Bulletin of the Seismological Society of America, v. 81, no. 5, p. 1424-1479.

Prentice, C.S., and Ponti, D.J., 1997, Coseismic deformation of the Wrights tunnel during the 1906 San Francisco earthquake: A key to understanding 1906 fault slip and 1989 surface ruptures in the southern Santa Cruz Mountains, California: Journal of Geophysical Research, v. 102, p.635-648.

Santa Cruz Public Libraries, 2005, Local history website [http://www.santacruzpl.org/history].

U.S. Geological Survey, 2005, Historic research in the Loma Prieta Area [http://quake.wr.usgs.gov/info/1906/historical_lp.html].

Wells, R.E., ed., 2004, The Loma Prieta, California earthquake of October 17, 1989—geologic setting and crustal structure: U.S. Geological Survey Professional Paper 1550-E, 204 p.

Wentworth, C.M., Black, M.C., McLaughlin, R.J., and Graymer, R.W., 1998, Preliminary geologic map of the San Jose 30 x 60-Minute Quadrangle, California: U.S. Geological Survey Open-File Report 98-795, 1 sheet, scale 1:100,000 [http://pubs.usgs.gov/of/1998/of98-795/].

4. Big Slide Trail, Forest of Nisene Marks State Park

Trip highlights: Epicenter of the 1989 Loma Prieta earthquake, landslides, fissures, sag ponds, deranged forest

The magnitude 7.0 Loma Prieta earthquake of October 17, 1989 occurred at 4:15 pm and lasted between 10 and 15 seconds. The epicenter was located in the Forest of Nisene Marks State Park (located about midway between Loma Prieta Peak and downtown Santa Cruz) (see fig. 3-1). The hypocenter (the point at depth where the rupture started) occurred at a depth of 11 miles (18 km), located approximately 4 miles (6 km) west of the surface trace of the San Andreas Fault (the fault plane dips at an angle of about 75 degrees to the west). The rupture of the earthquake propagated through the southern Santa Cruz Mountains for a distance of about 25 miles (40 km) in the area east of Highway 17. It was estimated that as much as 6.2 feet (about 2 m) of horizontal right-lateral displacement and 4.2 feet (1.3 m) of vertical (reverse) displacement occurred, with uplift on the west side relative to the east side of the fault. Debate still continues among scientists on whether the 1989 Loma Prieta earthquake actually occurred within the San Andreas Fault Zone (McNutt and Sydnor, 1990; Wells, 2004).

It is fortunate that the epicenter of this large earthquake happened in such a remote area within the Forest of Nisene Marks State Park. The hike to the epicenter region of the 1989 Loma Prieta earthquake is both long and strenuous, but the rewards are a multitude of views of a damaged landscape and a forest that is recovering from the effects of the earthquake. Shaking from the magnitude 6.9 Loma Prieta earthquake created numerous surface ruptures, sag ponds, and slumps that are still largely visible (figs. 4-1 to 4-3). The most impressive geomorphic features are along the Big Slide Trail that descends from China Ridge into the canyon of Aptos Creek.

Figure 4-1. This pond formed at the head of a great slump along the Big Slide Trail.

Figure 4-2. The landscape reveals many clues to the severity of the 1989 Loma Prieta earthquake. Many trees fell during the earthquake, and whole groves of trees have bent trunks from having adjusted themselves back to a vertical direction after the ground surface rotated in areas of deep-seated slumps.

Starting from the Aptos Creek Road (Santa Cruz) park entrance, park at the picnic area trail head and follow the Aptos Creek Fire Road uphill for about 4 miles (6.5 km). The hike involves an elevation gain of about 1,000 feet (300 m). The Big Slide Trail intersects the fire road on the right. This narrow trail descends gradually at first through a "deranged

Figure 4-3. One of many fissures that opened along the Big Slide Trail during the 1989 Loma Prieta earthquake.

Figure 4-4. The park sign was installed along the Aptos Creek Trail at the location of epicenter of the 1989 Loma Prieta earthquake. This sign is located about one mile east of the intersection of the Aptos Creek Trail with the Aptos Road (trail).

forest” or “drunken forest” (trees lean in unusual ways in many places; fig. 4-2). The trail then descends steeply into Aptos Creek Canyon in an area affected by massive landslides initiated, in part, by the earthquake. Continue downhill along the Aptos Creek Trail to return to the fire road. A sign marking the location of the epicenter is along the Aptos Creek Trail about 0.6 miles (1 km) east of the fire road intersection (fig. 4-4). The complete loop hike is about 11 miles (18 km). Note that the rugged Big Slide and Aptos Creek trails are inaccessible to bicycles. It is advisable to call about trail conditions before starting the hike during the rainy season.

The Forest of Nisene Marks was heavily lumbered, mostly to make charcoal for baking local marble into lime (for cement) in the late 19th to early 20th century. Wood and lime from the Santa Cruz area were used in the rebuilding of San Francisco after the 1906 earthquake and fire. Local lime was also used in the construction of the Grand Coulee Dam in Washington.

Selected References

McNutt, S.R., and Sydnor, R.H., eds.., 1990, The Loma Prieta (Santa Cruz Mountains), California, earthquake of 17 October 1989: California Division of Mines and Geology Special Publication 104, Sacramento, 142 p.

Wells, R.E., ed., 2004, The Loma Prieta, California earthquake of October 17, 1989—geologic setting and crustal structure: U.S. Geological Survey Professional Paper 1550-E, 204 p.

5. Lyndon Canyon and Lake Ranch Reservoir, Sanborn County Park

Trip highlights: San Andreas Rift Valley, Lake Ranch Reservoir (site of 1906 earthquake damage)

The hike to Lake Ranch Reservoir via Black Road is a scenic and easy walk (an unusual flat hike in the Santa Cruz Mountains). The trail basically follows the scarp of the San Andreas Fault to Lake Ranch Reservoir, a modified sag pond that straddles the pass between Lyndon Canyon on the south and Sanborn Creek on the north (fig. 5-1). The lake has two dams, one on each of the drainages at opposite ends of the lake. The hike, and the drive to get there, offers views of the San Andreas Rift Valley and provides a wilderness-like feel for a park relatively close to the greater urban San Jose area.

To get there take Highway 17 south toward Santa Cruz. Exit at Bear Creek Road about 3 miles (5 km) south of Los Gatos. At the top of the highway ramp continue straight (north) along the highway frontage road about 0.2 miles (0.3 km) and turn left (north) on Black Road. Black Road winds northward (uphill) and eventually connects with Skyline Boulevard (Highway 35) that runs along the crest of the northern Santa Cruz Mountains. About 2 miles (3 km) south of the intersection with the frontage road, Black Road crosses and then basically follows the San Andreas Fault Zone for a couple of miles. Although the landscape has been heavily modified by past and recent human activity, it is still possible to pick out landscape features that probably reveal the trace of the fault. Look for sag ponds (wet areas with cattails), isolated hills and linear ridges, straight stream valleys, steep escarpments (fault scarps), and changes in vegetation.

The trailhead for the John Nicholas Trail to Lake Ranch Reservoir is located about 6 miles (10 km) from the intersection of Black Mountain and the frontage road along Highway 17. The trailhead is located by a small parking area on the north side of the road about a mile downhill from the inter-

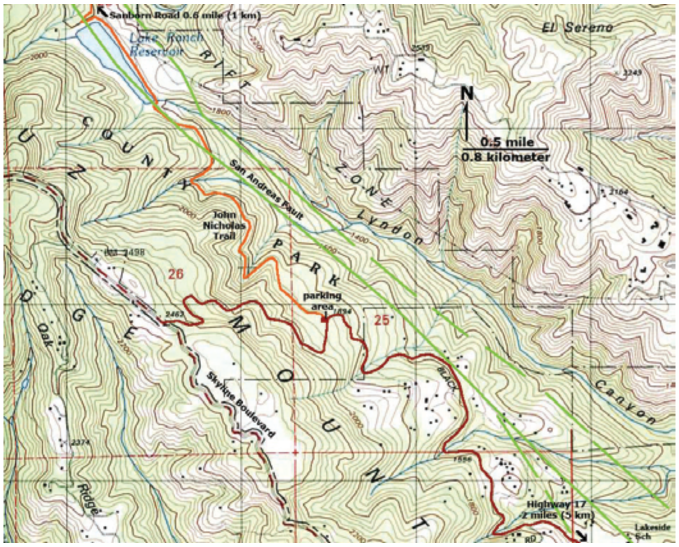


Figure 5-1. Map showing the location of the Lyndon Canyon-Ranch Lake Trail.

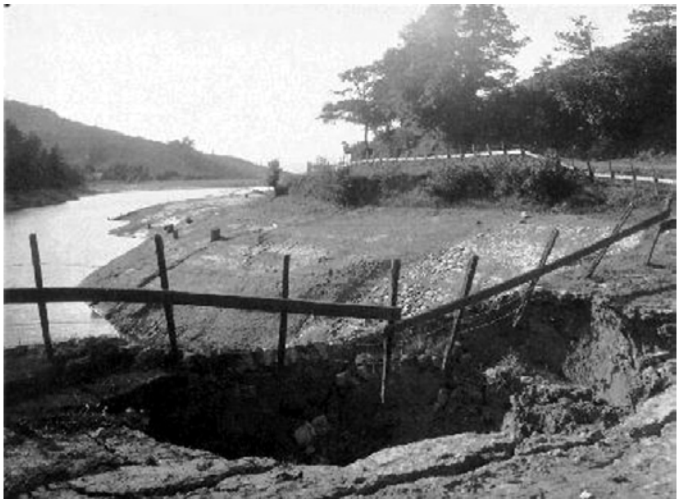


Figure 5-2. Ranch Lake as it appeared shortly after the 1906 San Francisco earthquake. Ground failure in the foreground is the result of slumping of the earthen dam at the south end of the lake. Local lore is that a large quantity of water splashed out of the lake as a result of the earthquake. Note the high water line that existed at the time of the earthquake. Also note the comparative lack of forest in the photo as compared to the modern image below. The main trace of the fault runs along the base of the hill on the left, but the whole lake is within the fault zone. (Photograph from Lawson, 1908.)

Figure 5-3. Ranch Lake as it appears today. The lake was originally used as a reservoir, but was abandoned after the 1906 earthquake for fear of flood disaster should the dam rupture during an earthquake. After nearly 100 years coniferous forests have returned to the hillsides west of the fault. Oak, bay laurel, madrone, and chaparral dominate the hillsides east of the fault. The difference in vegetation reflects both hillslope orientation (west-facing slopes tend to be warmer and dryer) and soil characteristics (bedrock characteristics influences soil development and moisture retention).

section with Skyline Boulevard. The hike to Lake Ranch Reservoir is 1.4 miles (2.2 km). The trail basically follows the uphill side of the San Andreas Fault scarp that follows Lyndon Canyon Creek (and is responsible for its linear valley). About 0.5 mile along the trail are two large redwoods that escaped the era of heavy lumbering of this region of the Santa Cruz Mountains at the close of the 19th century. A small spring-fed stream flowing past the redwoods produces a slight sulfur smell ("rotten eggs").

The trace of the San Andreas crosses through low earthen dams at both ends of Lake Ranch Reservoir. The area experienced surface rupture during the magnitude 7.9 1906 San Francisco earthquake (fig. 5.2). An additional 0.5 mile takes you to the south end of the lake where one of the headwater tributaries of Sanborn Creek descends from Castle Rock Ridge on the west. This stream probably flowed into Lyndon Canyon Creek in the past, but migration of Castle Rock Ridge northward (on the west side of the fault) relative to El Sereno Ridge (on east side of the fault) resulted in the formation of the straight valley of Lyndon Canyon Creek and then stream capture of the headwater stream by Sanborn Creek. Comparison of the photograph taken in 1906 with a recent photograph (figs. 5-2 and 5-3) demonstrate just how heavily lumbered the area was about the time of the 1906 earthquake.

Lake Ranch Reservoir is also accessible from a relatively steep trail that starts at the end of Sanborn Road about a mile south of the main entrance of Sanborn County Park (see chapter 6). This route climbs steeply up an access road to the reservoir for a distance of about 1 mile (1.6 km) before it reaches the northern impoundment of the dam. Parking is limited near the trailhead area at Sanborn Road.

Selected References

Brabb, E.E., Graymer, R.W., and Jones, D.L., 2000, Geologic map and map database of the Palo Alto 30' x 60' Quadrangle, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2332, 2 sheets, scale 1:100,000 [http://pubs.usgs.gov/mf/2000/mf-2332/].

Lawson, A.C., 1908, The California earthquake of April 18, 1906: Report of the State Earthquake Investigation Commission—Carnegie Institution of Washington Publication 87, 2 vols.

6. Earthquake Trail, Sanborn County Park: A Geology Hike Along the San Andreas Fault

Trip Highlights: San Andreas Fault, fault scarps, shutter ridges, sag ponds, landslides, fractured walls, offset streams, offset alluvial fan

Sanborn County Park straddles a section of the San Andreas Fault Zone where it passes through the Santa Cruz Mountains in Santa Clara County, California (fig. 6-1). This chapter is a guide to the Sanborn Earthquake Trail, a moderately strenuous hiking route that is 2.5 miles (4 km) long and leads through hilly terrain covered with a mixed redwood, Douglas fir, and oak woodlands and grasslands within the park and on other public land. The park area experienced strong earthquake shaking during the magnitude 7.9 1906 San Francisco earthquake and the magnitude 6.9 1989 Loma Prieta earthquake. The trail provides access to a variety of geomorphic features associated with the fault zone, including deflected streams, shutter ridges, sag ponds, fault scarps, and other fault-related landforms. Most of these landscape features are developed on an old alluvial fan system along streams draining from a high ridgeline eastward into the rift valley along the San Andreas Fault Zone. Other ongoing surface processes affecting the forested landscape include landslides, debris flows, floods, giant tree falls, and other forms of mass wasting and erosion, as well as both prehistoric and modern human activity that have left an imprint on the landscape. The route follows established park trails including the route of the biology-oriented Sanborn Nature Trail.

How to get to Sanborn County Park: From the north (San Francisco), take I-280 south toward San Jose. Exit to California Highway 85 south and proceed 3.5 miles (6 km) to the De Anza Boulevard exit. Bear right onto De Anza Boulevard

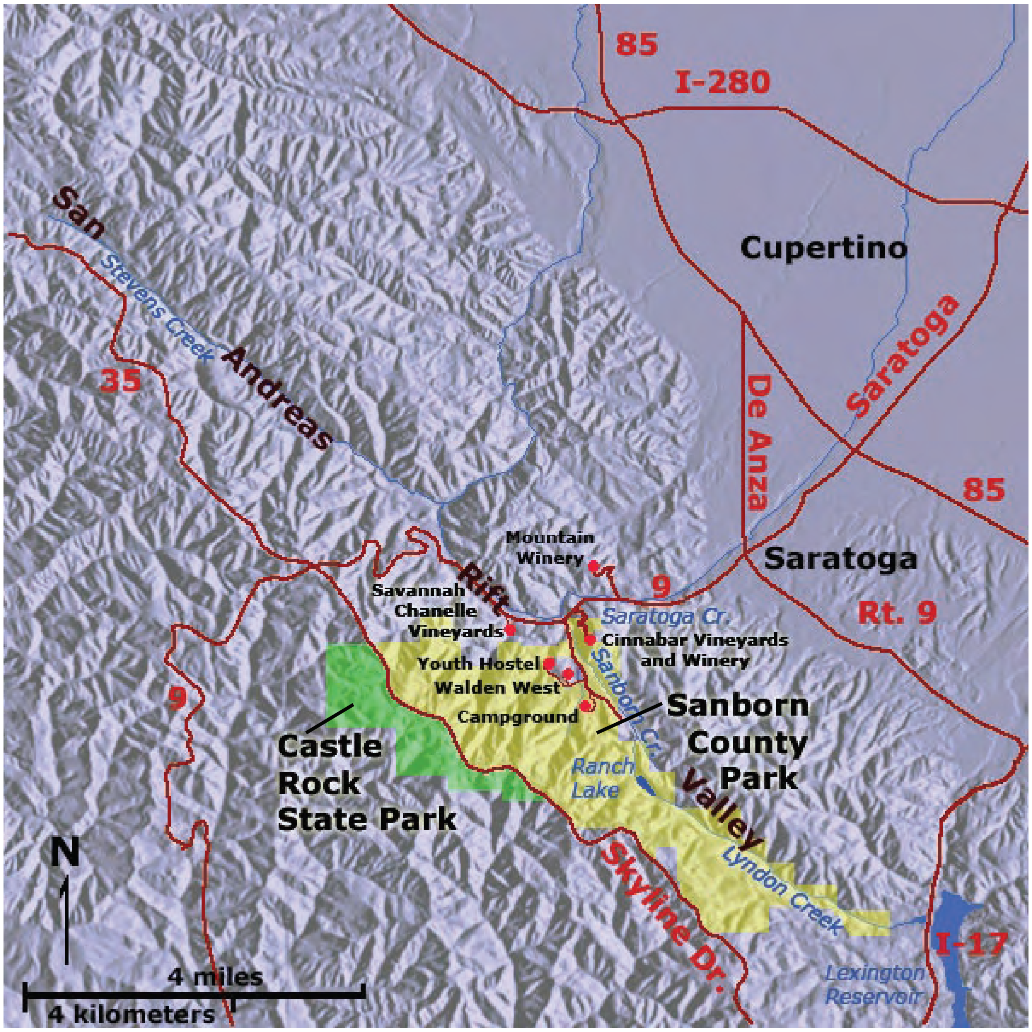


Figure 6-1. Map of the Sanborn County Park vicinity near Saratoga, California.

and proceed south 4 miles (7 km) to the intersection of Highway 9 in downtown Saratoga. From the south (San Jose), take California Highway 85 north and then take Highway 9 west to the town of Saratoga. Proceed west on Highway 9 (also called Big Basin Way or Congress Springs Road) through downtown Saratoga and proceed up Saratoga Canyon for about 3 miles (5 km). Turn left on Sanborn Road. Proceed 1 mile (1.6 km) to the entrance to Sanborn County Park on the right. A day-use fee ($5) is required for each vehicle entering the park. After passing the Entrance Station follow the main park road uphill to the RV Campground parking area. If day-use parking spaces are not available in the RV area use the day-use parking lot just below the RV campground. Field-trip participants should gather near the trailhead to the walk-in campground near the RV campground restroom facility.

Warnings for hikers: Please be aware that poison oak, ticks, rattlesnakes, mountain lions, or other natural hazards can be encountered in the park (as anywhere in the Santa Cruz Mountains). Rattlesnakes are generally harmless unless provoked (fig. 6-2). Simply take another route if you encounter one, and warn others in the area to be aware. Rattlesnakes are most likely to be seen near water sources on hot summer days. All wildlife in the park is protected. Slick trails, falling branches from trees, and stream flooding may be potential hazards during storms. Pets and smoking are not allowed on park trails. Bring some water on the hike.

Sanborn Earthquake Hike—Geology Field-trip Route

Figure 6-3 shows the route of the recommended hike. Numbered and lettered dots on the map show the general location where stops for observation are located. However, field-trip participants should be on the lookout for wildlife and additional natural features not mentioned in the text. The complete field-trip hike described below typically takes 4 to 5 hours with a mixed group of people of all ages. This includes time for discussion and a picnic in the park after the walk

Figure 6-2. A western diamondback rattlesnake warms itself in the morning sun on a Sanborn County Park trail.

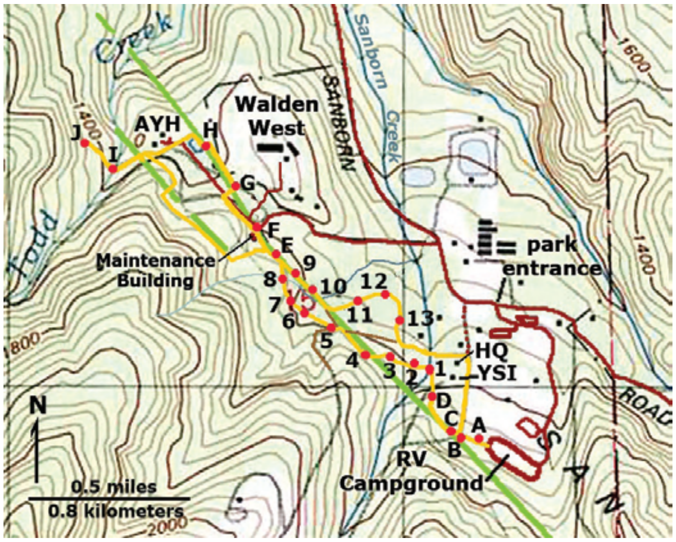


Figure 6-3. Map of a portion of Sanborn County Park with the route of the Earthquake Trail shown in gold with numbered and lettered stops in orange. Stops are organized as both letters (A-J) and numbers (1-13). The letter stops of the Earthquake Trail were added to incorporate the preexisting numbered stops of the already established Sanborn Nature Trail. Each of the stops is marked by a lettered- or numbered-trail stop post. The trace of the San Andreas Fault is shown in green. Park access roads are shown in red. The base map is a U.S. Geological Survey topographic map showing elevation contour lines in feet. The hike begins at a kiosk with park rules and regulations near the RV campground restrooms. AYH, American Youth Hostel; HQ, park headquarters; YSI, Youth Science Institute.

Stop A is located near several large sandstone boulders about 100 feet (30 m) downhill of the intersection of two paved trails near the RV campground restroom facility. This first stop is located at the edge of the large field that provides one of the best views of the park vicinity. Landscape features visible from this location include:

The San Andreas Fault: It may not be evident to most people who visit Sanborn County Park that they are, in fact, in the San Andreas Fault Zone. The fault passes through this portion of the Santa Cruz Mountains in and around Sanborn Park. The San Andreas Fault extends from great depths estimated from seismic data to be in the range of about 9 to 12 miles (15 to 20 km) under the Santa Cruz Mountains (Jachens and Griscom, 2004). As the fault zone approaches the surface it splays into a complex system of both parallel and interconnecting faults. The San Andreas, Hayward, Calaveras, and other earthquake faults are all part of the greater San Andreas Fault system (fig. 6-4). In the San Francisco Bay region, the

San Andreas Fault system displays a total offset of about 286 miles (460 km), but only about 87 miles (140 km) of this offset occurred along the San Andreas Fault in the central Santa Cruz Mountains, the rest of the offset occurred on the Hayward and Calaveras Faults in the East Bay region and on other regional faults (Dickinson, 1997; Graymer, 2002).

The San Andreas Fault is not perfectly straight. In places, such as in the Santa Cruz Mountains, the fault trace bends slightly to the left. This bend causes uneven forces throughout the crust and results in the ongoing uplift of the Santa Cruz Mountains. Gradual changes in elevation are occurring continuously throughout the Coast Ranges, both upward and downward with the build up of pressure and its release during episodic earthquakes. Fission track studies and other data demonstrate that rock in the Santa Cruz Mountains has risen approximately 2 miles (3.2 km) over the past 4.7 million years (a rate of about 0.6 mm per year) (Bürgmann and others, 1994). Since the highest elevations in the Santa Cruz Mountains are only slightly higher than 0.63 mile (1 km), the rate of erosion of the mountain uplands is therefore about 0.4 mm per year. However, uplift and erosion factors are complex, and they are neither uniform nor synchronous throughout the Santa Cruz Mountains.

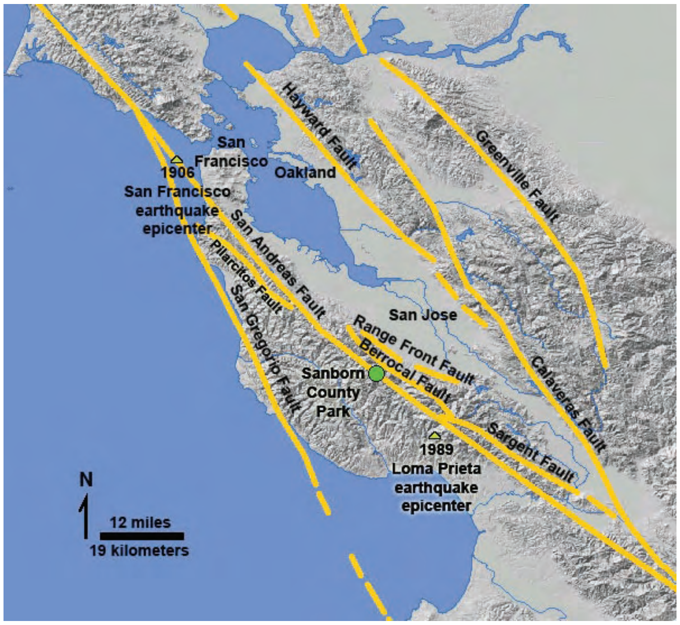


Figure 6-4. The San Andreas Fault system in the San Francisco Bay region. The San Andreas Fault is a relatively new geologic feature in the San Francisco Bay region. It began forming in the south central California region about 28 million years ago but propagated through the Bay Area region only about 10 to 6 million years ago (Elder, 2001). Prior to the San Andreas Fault, a completely different continental margin configuration existed in California. Traditionally, the San Andreas Fault has been used to separate the North American Plate on the east and the Pacific Plate on the west in California. The offset along the San Andreas Fault is a strike-slip fault with right-lateral offset, such that the west side (the Pacific Plate) is moving northward relative to the east side (the North American Plate). (A USGS publication entitled *This Dynamic Earth* provides an introduction to plate tectonics theory; it is on-line at http://pubs.usgs.gov/publications/text/dynamic.html.)

The San Andreas Rift Valley: Sanborn Creek is a headwaters tributary of the greater Saratoga Creek watershed that drains along Highway 9 into Saratoga. Over time, streams have carved a canyon that follows the zone of crustal weakness associated with the San Andreas Fault Zone. The combination of stream erosion and movement along different faults near the surface has resulted in the formation of the San Andreas Rift Valley; it is both a "geologic-structural" valley, and "surface-erosional" valley. The landscape is a reflection of two totally different geologic processes—(1) tectonic forces affecting the Earth's crust below ground and raising the land surface and (2) the combination of erosional and depositional processes occurring at the land surface. However, the structural forces are, in part, controlling how and where erosion and deposition are occurring in the park area. The combined headwater valleys of Sanborn Creek, Lyndon Creek (to the south), and Saratoga and Stevens Creek define the trace of the San Andreas Rift Valley in the central Santa Cruz Mountains (see fig. 6-1).

The gap in the hills to the south of the campground marks the location of the active trace of the San Andreas Fault. The steep slope above the RV campground is a fault line scarp. However, in most places on the steep slope the fault is covered by colluvium and does not show an obvious surface expression to point to its exact location on the slope. Note that the exact fault location is not always easy to see. In most places, the surface expression of the San Andreas Fault is complex. Slumping and landsliding occur along the fault in many areas where it crosses slopes. In addition to the main (or active) trace of the San Andreas Fault, there are many other faults in the area, some of which display evidence of recent movement.

Bedrock Geology: Figure 6-5 is a portion of a geologic map showing the Sanborn County Park area (Brabb and others, 2000). The bedrock west of the San Andreas Fault consists of Tertiary-age sedimentary rocks (roughly 40 to 30 million years) that probably overlie more ancient Salinian granitic basement rocks at depths of about 4 miles (6 km) below Castle Rock Ridge. On the hillsides to the east of the San Andreas Rift Valley (toward Saratoga) the bedrock consists of oceanic basement rocks and associated younger sedimentary rocks (Coast Range Ophiolite and Franciscan Complex, roughly 165 to 120 million years old). With the uplift of the Santa Cruz Mountains, erosion of bedrock on the mountainsides on both sides of the San Andreas Fault contributed sediments that partially filled in the San Andreas Rift Valley. Figure 6-6 is a generalized geologic cross section across the park area between two mountain ridges that border the rift valley—Castle Rock Ridge on the west and El Sereno on the east.

Alluvial Fans: The sloping fields in the main park area are part of a system of alluvial fans associated with streams draining from Castle Rock Ridge to the west. Over thousands of years, sediments eroded from the steep slopes above were deposited on the more level slope in the valley below. Alluvium is unconsolidated material on the land surface, including soil, boulders, and sediments deposited by wind and water. An alluvial fan is a wedge-shaped accumulation of stream-deposited sediments that spreads out into a valley from a canyon source area, such as in a valley along a fault-bounded highland area. Where many alluvial fans join together along a mountain front the result is a broad, apron-like, sloping, alluvium-covered surface called a bajada. Much of Sanborn Park is located on an old alluvial fan complex (or bajada) that is currently being incised by streams. The surface of the fan is highly irregular from stream erosion and from offset along the the San Andreas Fault which cuts across the alluvial surface.

Stop B is located at the intersection of trails near a park information kiosk just north of the campground restrooms.

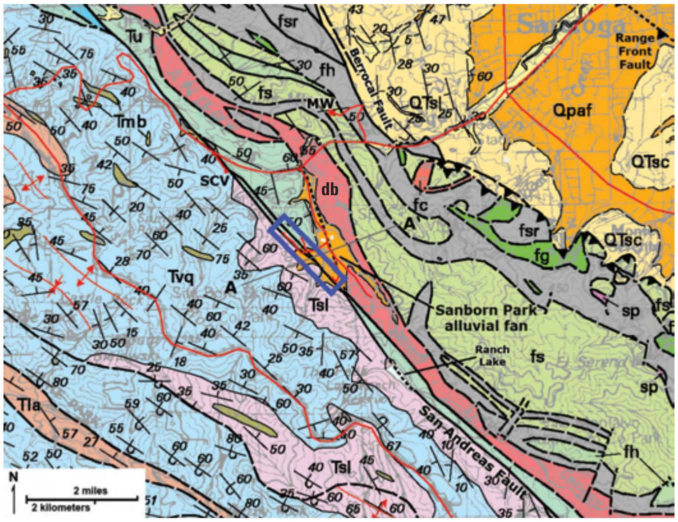


Figure 6-5. Geologic map of the area encompassing Sanborn County Park (from Brabb and others, 2000). The blue box at the center of the figure shows the Earthquake Hike field area in Sanborn County Park. SCV is the Savannah-Chanelle Vineyards; MW is the Mountain Winery. Map units include; Qpaf, Quaternary (Pleistocene) alluvial fan deposits; QTsc, Santa Clara Formation (gravel, sand, and mud of Pliocene and early Quaternary age); QTsl, lake beds. Franciscan Complex (undivided) and other rocks east of the San Andreas Fault include: fsr, sheared rock (mélange); fg, greenstone; fh, argillite and shale, some sandstone; fs, sandstone; fc, chert; sp, serpentinite; db, diabase and gabbro (Coast Range Ophiolite); Tu, Unnamed Tertiary mudstone, shale, argillite and sandstone (Eocene?). Tertiary marine sedimentary rocks west of the San Andreas Fault include: Tla, Lambert Shale (lower Miocene and Oligocene); Tmb, Mindego Basalt and related volcanic rocks (lower Miocene and Oligocene); Tvq, Vaqueros Sandstone (lower Miocene and Oligocene); and Tsl, San Lorenzo Formation (Oligocene and upper and middle Eocene), consisting mostly of shale and mudstone. A to A′ shows the location of a geologic cross section illustrated in figure 6-6. Line symbols with associated numbers represent the strike direction and dip angle of mapped rock units. Map modified from Brabb and others, 2000.

Note the abrupt change in slope near the kiosk and trail-intersection area. This break-in-slope at the top of the alluvial fan is the fault-line scarp of the San Andreas Fault. Three low pyramid-topped posts with red bands just south of the Stop B post mark the most likely location of the San Andreas Fault. Whether or not there was surface rupture here from the 1906 earthquake is uncertain because no reports from the 1906 were made at this location. However, there almost certainly was surface rupture, if not exactly where the posts are, then very close by. Without a recent major earthquake, or trenching, the exact locations of faults in this area are not clearly visible. Surface erosional processes have erased evidence of surface rupture along the fault trace. There could be more than one seismically active strand of the fault in this valley.

The amount of surface rupture in the southern Santa Cruz Mountains caused by the Great San Francisco earthquake of April 18, 1906, is uncertain but probably varied between 3 to 10 feet (1 to 3 m) of right-lateral offset. The best reported observation was 5 feet (1.5 m) of right-lateral offset in Wrights Tunnel (south of Lexington Reservoir) (Prentice and Schwartz, 1991); however, analysis of historical documents show that the tunnel was offset a total of at least 5.6-5.9 feet (1.7-1.8 m) (Prentice and Ponti, 1997); the main trace of the San Andreas Fault has been mapped east of the trail entrance (McLaughlin and others, 2001). Many of the ground ruptures in the southern Santa Cruz Mountains found after both the 1906 and 1989 earthquakes were a result of landslides induced by ground shaking (Prentice and Schwartz, 1991). Nearly all the trails, roads, and manmade structures in the park area were constructed after the 1906 earthquake.

The greatest offset reported the 1906 earthquake occurred well north of the SF Bay region, with 16 feet (5 m) of right-lateral offset well documented near Point Arena, and 20 feet (6 m) reported near Point Reyes. Some reports of greater offsets were reported, but these measurements, including those at Point Reyes are uncertain, and may include non-tectonic

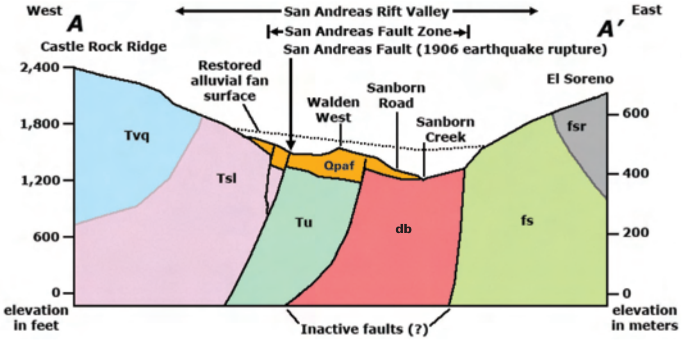


Figure 6-6. Generalized geologic cross section of the San Andreas Rift Valley between Castle Rock Ridge and El Sereno (ridge). The location of the cross section is shown as A to A′ on figure 6-5. The subsurface character of the faults and bedrock are inferred from mapped features in the surrounding area. The diagram also illustrates the differences in the use of the terms San Andreas Fault, San Andreas Fault Zone, and San Andreas Rift Valley. See figure 6-5 for abbreviations.

displacement due to ground shaking and lateral spreading, or by slumping. Southward into the Santa Cruz Mountains, the amount of offset reported after the 1906 earthquake diminished to about 1.2 meter (4 ft) near Watsonville, to almost nothing observable on the surface south of San Juan Bautista, although tremendous seismic shaking was reported over a much greater region extending far to the south in the vicinity of Pinnacles National Park. Subsurface rupture along the fault probably extended well beyond the region of surface rupture (http://quake.wr.usgs.gov/info/1906/offset.html; Gilbert and others, 1907; Lawson, 1908).

Stop C marks the beginning of a narrow path that leads downhill along the escarpment of the San Andreas Fault into the drainage of Sanborn Creek. The escarpment marks the west side of the San Andreas Fault. On the east side of the fault near the trail intersection is a large water tank constructed by the Santa Clara County Water District that was built for irrigation and emergency purposes in the park. The tank was constructed in 2003 on a small hill on the east side of the fault.

This undeveloped section of the trail is inaccessible when wet. If the trail is closed, proceed down and pick up the route at the Visitor Center/Youth Science Institute (YSI) and continue on the hike from there.

The trail leads several hundred feet downhill through a grove of small redwoods. The ecosystem around Sanborn Park includes redwood and Douglas fir forests in the cooler, wetter valleys and north- and east-facing slopes, whereas chaparral and shrub oak dominate the higher, dry west-facing slopes. Large redwood stumps along the trail and throughout the park show that the area was heavily lumbered in the late 19th century.

Keep looking to the north through the gaps in the forest to where Sanborn Creek descends off of the escarpment of the San Andreas Fault. Just north of an “artificial” waterfall created by a pipe diversion of Sanborn Creek, the natural stream has been deflected where it encounters the fault. It makes a sharp turn and flows northwestward along the fault for some distance before turning right to resume its initial eastward downstream course in its incised valley. The bend in the stream is due to stream capture as the western (uphill) side of the San Andreas Fault moved northward relative to the alluvial fan (downhill) side of the fault. Over time, the stream has continued to flow in its current channel resulting in a dog-leg shaped path of the stream channel called an deflected drainage. This zigzag-shaped bend shows that the course of Sanborn Creek has been affected by the right-lateral relative motion along the San Andreas Fault. Much of the landscape geomorphology in Sanborn Park is related to the formation of offset drainages and stream capture along the San Andreas Fault.

Stop D is located near some very large boulders where the narrow path intersects a larger park trail. Some springs are located nearby in a low area to the south of the stream. Springs are common along fault zones because faults and fractures serve as fluid-migration pathways. Whether these springs are related to a fault is uncertain.

How did the large boulders get here? The boulders are derived from the Vaqueros Sandstone or the San Lorenzo Formation. Both of these sedimentary rock formations occur as bedrock in the hillsides to the west and above Sanborn Park. The Vaqueros Sandstone is the dominant cliff-forming unit in Castle Rock State Park, located along the ridge west of Sanborn Park. These large blocks of sandstone were carried downslope onto the alluvial fan by rock falls, landslides, or debris flows from the upland areas to the west, If they were transported by a landslide or debris flow, the smaller rock fragments and mud would have surrounded these boulders, but must have long since eroded away. Large boulders are a typical occurrence on the upper portion of alluvial fans. Another possible explanation is that the huge boulders were dislodged during a large earthquake on the San Andreas Fault and rolled down the steep slope and across the fault.

The Vaqueros Sandstone (lower Miocene and Oligocene, roughly 20 to 30 million years old) consists of light-gray to buff, fine- to medium-grained, locally coarse-grained arkosic (feldspar mineral-bearing) sandstone interbedded with olive- and dark-gray to red and brown mudstone and shale. Sandstone beds are commonly from 1 to 10 feet (0.3 to 3 m) thick and mudstone and shale beds are as much as 10 feet (3 m) thick. In the region, the Vaqueros Sandstone varies from several feet to as much as 2,300 feet (700 m) in thickness (Brabb and others, 2000). The formation consists of sediments that were probably deposited in a shallow marine shelf environment, offshore of a river mouth that was probably far to the south (possibly in southern California). These sediments, now rock, where transported northward to their present location by movement along the San Andreas Fault system.

The San Lorenzo Formation (Oligocene and upper and middle Eocene, roughly 30-to-50 million years old) consists of dark-gray to red and brown shale, mudstone and siltstone, with local interbedded layers of sandstone, and is about 1,800 feet (550 m) thick. Within the upper part of this formation are large, elongate carbonate concretions. The presence of shale indicates that the formation represents materials deposited in somewhat deeper water, a setting farther offshore than the younger Vaqueros sediments.

Volcanic rocks are present in the hillsides west of the fault with outcrops and boulders scattered throughout the Santa Cruz Mountains. The Mindego Basalt (Miocene and Oligocene) includes both extrusive and intrusive volcanic rocks that range in color from dark-gray to orange-brown to greenish gray breccia, tuff, pillow lavas, and flows. The intrusive rocks tend to be coarsely crystalline. Radiometric dates of selected samples yielded an age of about 20.2 (+/-1.2) million years (Brabb and others, 2000).

Along the San Andreas Fault, these rock units are highly fractured and mixed together. Cobbles and boulders of basalt can be found in the alluvial sediments along streams in the park area. Fossils are not common in either the Vaqueros or San Lorenzo formations locally. Collectively, the rocks on the west side of the fault in Sanborn Park are between 20 and 50 million years old, whereas the rocks on the east side of the fault are much older. The later belong to the Franciscan Complex, a mix of ancient marine sediments and oceanic crustal rocks that formed in the mid- to late-Mesozoic era, roughly between 200 to 100 million years ago (Elder, 2001). Franciscan rocks are not exposed along this field-trip route.

Continue downhill and then bear to the right, avoiding the private residence (a post with an arrow marks the route). Proceed downhill; once you get to the paved road, take the wooden bridge across a small pond and then proceed uphill to the left to the Visitor Center (Youth Science Institute building near the Park Office).

Local legend says that the shaking caused by the 1906 earthquake caused much of the water to splash out of the pond in this area. Note that much of the landscape here has been modified since the earthquake. A significant portion of the water in Lake Ranch Reservoir (at the south end of the park) was also reported to have splashed out during the earthquake (see chapter 5). The reservoir lies in a modified natural sag pond along the San Andreas Fault in the natural upland saddle between the drainages of Sanborn Creek (on the north) and Lyndon Creek (canyon to the south).

Nature Center /Youth Science Institute—Optional Stop

Park maps and brochures are available at the Nature Center/Youth Science Institute (YSI). Several displays highlighting local Native American (Ohlone) culture and history are located on the outside patio area of the Nature Center. A number of artifacts are on display. Other exhibits include live animals that populate the Santa Cruz Mountains, earthquake and geology displays, an insect zoo, and a garden featuring native plants and plants used by Native Americans. The YSI is an educational institution that conducts a variety of prekindergarten to high school and teenage group programs, after school science classes, and summer science camps (with similar programs at Vasona and Alum Rock County Parks).

Geology Along the Sanborn Nature Trail

From the Nature Center/YSI, the Earthquake Hike follows the same route of the Sanborn Nature Trail. Biology-oriented nature-trail brochures are available from the park office and at the Nature Center/YSI. Near the Visitor Center, a sign points to the "Peterson Memorial Trail, San Andreas Trail, and Walden West." Follow the trail downhill past some big blocks of sandstone to a recently renovated stage area. The bridge across Sanborn Creek is at Stop 1 on the Nature Trail route.

Stop 1 along the nature trail is devoted to a coastal redwood, the California State tree. Coastal redwoods can grow more than 320 feet (100 m) high and can live more than 2,000 years. The red bark of the redwoods contains a resin that helps protect them from fire. They also are able to reproduce through their root system when cut down or damaged by fire. Most of the redwoods in the park are younger than a century because the area was heavily lumbered in the late 1800s. The remnants of old logging trails are still visible in many places. These road scars can now serve as a measure of landscape change and forest recovery over time, and many now serve as hiking trails through the park.

At the wooden bridge, note the incised character of the stream valley (Sanborn Creek, a tributary of Saratoga Creek along Highway 9). Also note the abundance of large sandstone boulders in the creek bed. Signs describe the creek bed area as a "restoration area" to repair damage from past heavy foot traffic off the trails. The small stream has cut down into an older surface of the alluvial fan. Note that near Stop 1 a narrow flood plain forms the floor of this stream gorge and that the small stream is limited to an irregular channel incised into this flood plain. The floodplain can be completely covered during floods or especially when debris flows occur.

Proceed steeply uphill from the bridge along the Nature Trail. From here, the trail follows ascends the alluvial fan along the north side of the incised ravine of Sanborn Creek and includes stops 2, 3, and 4.

Stop 2 is located on a flat area, (possibly an old stream terrace) above the incised valley of Sanborn Creek. This stop in the Sanborn Nature Trail guide points out the differences between a redwood and a Douglas fir. Both trees are used for lumber. However, Douglas firs are also currently farmed as Christmas trees throughout the Santa Cruz Mountains.

Stop 3 is a good area to examine the character of the old alluvial fan surface. Note the gentle slope to the east and the abundance of rock material on the surface between the trees. All the material beneath the surface is poorly consolidated alluvium deposited by stream processes, landslides, slumps, debris flows, floods, rockfalls, and creep from the hill slope above before the modern forest developed. Erosion has removed most of the finer sediment from around the largest boulders resulting in their concentration on the surface of the old alluvial fan.

Stop 4 is located where the trail approaches the steep escarpment at the top of the Alluvial fan. Note, however, that there is no stream at the head of the fan! The source of the alluvial fan sediments has been displaced to the northwest by motion on the San Andreas Fault. The fault probably crosses the trail at a notch on the south side of the trail where the park has posted a sign designating an area closed for restoration. While walking along the trail beyond this point, note how some of the small drainages were abandoned as the streams' headwater areas moved northwestward over time relative to the alluvial fan. Past great earthquakes in this area have produced surface displacements measurable in many feet. Such shifts in ground motion assist "stream capture" or "stream deflection" and results in the development of new drainages and the abandonment of others.

Stop 5 is located at the intersection of the Nature Trail and the Peterson Memorial Trail. In the Nature Trail guide Stop 5 is a good location to learn to differentiate Blackberry plants from Poison Oak. Both plants have has leaves with 3 rounded or oak-like leaflets. However, Poison Oak is an upright shrub or climbing vine with drooping leaves. Small white flowers in the spring give way to white berries in loose clusters along the stem in the summer to fall seasons. In the fall the leaves can turn bright red. Blackberries and other berries are easy to confuse with Poison Oak because they are also shrub size and have leaves consisting of 3 leaflets. However, berries have stiff protective hairs on the leaves, stems, and the branches, and some have thorns. A simple phrase to remember the difference between the two plants is “Leaves of three, let it be. If it’s hairy, it’s a berry.”

Poison oak is abundant everywhere in the Santa Cruz Mountains. Although the plant foliage is most toxic, the barren branches, fallen leaves in winter months, and soil around the plants still can cause serious reactions in some people. Smoke from burning brush can carry the toxic resins. Simply washing laundry may not be enough to remove toxic resins from clothing, although for most people this is sufficient. The best solution to the poison oak problem is to learn to recognize and avoid the plant in all seasons.

In the vicinity of the trail intersection, note that the Peterson Memorial Trail to the right (downhill) follows an incised valley that does not have an actively flowing stream (fig. 6-7). This valley is an example of an abandoned stream—cut off from its headwater area due to motion along the fault.

Follow the Patterson Memorial Trail uphill a short distance to where the Nature Trail continues on the right. After the trail intersection, the Nature Trail traverses part of the fault scarp of the San Andreas Fault. Although most of the relative displacement along the fault is horizontal, right-lateral, strike-slip motion, part of the motion is also vertical in this area (contributing to the uplift of the Santa Cruz Mountains). In general, for every 10 feet the west side of the fault moves northward, the Santa Cruz Mountains also rise about 1 foot. It is also important to note that relative motion is not uniform everywhere along the fault (or faults), which adds to the complexity of the evolving landscape. In most places the trace of the fault is not easy to see except relatively soon after a major earthquake when surface rupture along the fault is commonly visible. Erosion and shifting surface sediments typically mask the traces of surface rupture within a few years.

Stop 6 is at a massive stump of a redwood harvested in the 1800s. This tree was about 1,000 years old and probably about 260 feet (80 m) high when it was cut. During its lifetime the tree probably experienced several major earthquakes, and in the course of its lifetime the land it occupied probably moved as much as 56 feet (17 m) northwestward relative to the opposite side of the fault! (This estimate is based on right-lateral slip rates along the local section of the San Andreas Fault by McLaughlin and others, 1999.)

Stop 7 is near the location of a large Douglas fir that fell during a storm in 1995. Note the abundance of rock material tangled in its decaying roots. This fallen tree is a testament to the erosional forces created by biological activity. The hummocky character of the forest landscape is partly a result of tree falls in the past. Other forces affecting the hillside are the constant seasonal wetting and drying, causing clays in the soil to expand and contract and gradually causing materials to

Figure 6-7. A park trail near Stop 4 follows a beheaded stream channel formed by right-lateral fault motion and stream capture. Unlike at Stop 1, there is currently no active stream channel to match the size of this valley. The escarpment of San Andreas Fault is to the right.

Figure 6-8. A stump of a great redwood harvested in the late 19th century. Note the offspring of the original tree on the uphill side of the stump. The tree was probably about 1,000 years old when it was harvested. Three youngsters for scale.

creep down slope. During colder periods in the past, freezing and thawing of the land surface probably also generated significant amounts of ground movement and supply of sediment to the alluvial fan. Combined with the force of gravity, weathered rock and soil migrates down slope over time, these processes are collectively called mass wasting.

Stop 8 is by a small wooden bridge over another small stream that crosses a strand of the San Andreas Fault. Many of the small streams in this area tend to dissipate as they approach and cross the fault. The flat area downslope is in part an ephemeral sag pond. A sag pond is a fault-related low area where water may accumulate because (1) sedimentation cannot keep pace with the tectonic forces warping the landscape downward or (2) erosion cannot keep pace with uplift blocking a drainage outlet. Between Stop 8 and the next stop (Stop E) notice the abundance of large boulders scattered on the surface throughout the forest. These massive boulders were transported downslope by rockfalls, landslides, or debris flows from the eastern mountain front of Skyline Ridge and deposited on the alluvial fan surface.

Figure 6-9. A fairy ring of redwoods at Stop E. After a mature redwood dies or is cut down, offspring chutes may sprout from the parent tree's roots. The original stump gradually rots away, leaving a ring of trees around the perimeter of the parent tree. There are several large and developing fairy rings along the trail route.

Northern Sanborn County Park Area

At the trail intersection beyond Stop 8, leave the Nature Trail temporarily. Turn left and proceed northward along the trail toward Walden West and the American Youth Hostel (Welch Hurst House). From this point the trail basically follows the trace of the San Andreas Fault. (**Note:** Do not follow the "San Andreas Trail"—this trail does not follow the San Andreas Fault, but instead leads uphill to the Skyline Boulevard area near Castle Rock State Park; a lower section of this trail is part of an optional return route after Stop J described below).

Stop E is located near two large "fairy rings" on the right side of the trail (fig. 6-9). These circular groves of redwoods formed when a large "parent" tree died (or was cut) and a ring of new trees sprouted around the base of the missing tree. Also note the low rocky linear ridge along the right side of the trail as you approach the park maintenance buildings (on the left). This is a "shutter ridge" formed by strike-slip motion along the San Andreas Fault (fig. 6-10).

Stop F is located at the intersection of the trail with the paved road. The road splits here to the park maintenance area, Walden West, and continues northwestward to the American Youth Hostel. The San Andreas Fault passes through this vicinity. Take time to look at the stone walls and stream culverts in this area. One of the pillars just downhill of the intersection displays a date of 1955 with a geology pick commemorating Vernon Pick, a successful Utah uranium prospector who temporarily owned this land.

Look for recent cracks, fractures, and right-lateral offsets in the stone walls that may be a result of earthquake damage (an example is shown in fig. 6-11). However, not all damage to the walls and culverts in this area may be from earthquakes; some could be from slumping, tree-root breakage, or other causes related to gravity-driven "mass-wasting creep." Earthquake shaking can cause ground ruptures that are not tectonic. This segment of the San Andreas Fault is considered "locked" since the 1906 earthquake, unlike other faults in the region that show evidence of slow movement or "creep." Different segments of the regional fault system are "locked" or "creeping" and although all fault segments are potential sites for

Figure 6-10. The trail follows a shutter ridge along the San Andreas Fault between Stops E and F near the Sanborn County Park maintenance facility. The shutter ride is on the right side of the trail. The slope to the left is part of the old alluvial fan along the mountain front of Castle Rock Ridge.

Figure 6-11. This culvert built by Vernon Pick in 1955 displays evidence of right-lateral displacement, possibly from ground motion (creep) along the San Andreas Fault. The arrows on this image show where to look for fractures and offset. Fractures and traces of offset are visible at both ends of the culvert.

large damaging earthquakes, the locked segments are locations where pressure will be released in potentially large, damaging earthquakes in the future (as has often occurred in the past). The Sanborn County Park area experienced heavy shaking during the 1989 Loma Prieta earthquake, but no fault surface rupture was observed in the vicinity.

Mr. Pick named the land Walden West and for a time developed an underground uranium ore testing facility and bomb shelter farther up the road (this underground structure was later abandoned and sealed off for public safety concerns). Local legend says that shortly after building his laboratory Mr. Pick chose to abandon his homestead to seek tax-exempt freedom outside of the United States. The County then purchased the land in 1977 for inclusion in Sanborn County Park. Walden West is an outdoor education and summer day camp under the direction of the Santa Clara County Department of Education.

Figure 6-12. The trace of the San Andreas Fault runs through an abandoned field near Walden West. In the past, the field was a sag pond that was drained and used as an orchard. In the more distant past, Todd Creek drained across this area before stream capture occurred and altered the stream's path to its modern drainage to the north of the field. The headwater valley of Todd Creek can be seen in the top of this image.

Downhill from the intersection, the road follows a stream valley that was once been the channel of Todd Creek—another case of an abandoned channel and stream capture due to offset along the fault. Because of more recent stream capture, Todd Creek now drains north of the large field below Walden West (located on the hilltop on the right). The broad field area was once the floodplain of Todd Creek, and in the past was partially occupied by a natural sag pond that has been modified and enlarged (fig. 12, see also figure 17 below). Since the 1906 earthquake, this field was drained and used as an orchard. The intersection at the south end of the field basically marks a stream divide between headwater areas of Sanborn Creek (to the south) and Todd Creek (to the north). As you will see as you continue the hike, Todd Creek has captured the stream drainage around this former sag pond area.

Stop G is in the field along the road leading to the American Youth Hostel. Follow the dirt trail from the stop G sign post out to a line of three red pyramid-topped posts. The three posts mark the known location of the San Andreas Fault.

An exploratory trench was dug in this location by the USGS to help characterize past earthquake activity of the San Andreas Fault. Although the trench exposed the trace of the fault, unfortunately, agricultural activity in the field in the last century had disrupted the surficial deposits that might have provided information about the frequency of earthquakes in this area over the past few centuries. This information can be used to make judgments about the frequency of future earthquakes along the fault. The difference between a "fault" and an "earthquake fault" or "active fault" is that the latter shows evidence of fault movement during the Holocene (the current geologic epoch that began roughly 11,500 years ago following the last ice age of the Pleistocene Epoch). Not all faults are in the San Francisco Bay region are considered active faults.

Stop H is located farther down the trail at an intersection with another trail connecting the playing fields at Walden West to a pond surrounded by a redwood forest. Note the drop from the field to the creek below. Although this area has been heavily modified over the years, it still reflects the character of the natural sag pond that existed here in the past. The trace of the San Andreas Fault runs through this pond area. The Stop H area provides a reasonable view to the north across the valley of Saratoga Creek and northwest along the trend of the San Andreas Rift Valley toward Table Mountain and the more distant grass-covered peak of Black Mountain located within the Monte Bello Open Space Preserve. Note the abundance of chaparral growing on the south facing slopes of Table Mountain.

Continue along the trail around the pond. Turn right on the paved road toward the American Youth Hostel.

The American Youth Hostel is a log-style house with a large hexagonal central room that was originally named Welch-Hurst House and was built in 1908 as a summer home for the Honorable Judge James Welch and his family. In 1955, the Welch Hurst House and surrounding lands were sold to Mr. Vernon Pick. When the house and land was later sold to the county, renovation costs were considered too high and the house was slated for demolition. However, the Santa Clara Valley hostelling club saved and renovated the building through a grassroots collective effort beginning in 1979. The Sanborn Park Hostel is now listed on the National Registry of Historic Places (http://www.sanbornparkhostel.org/about.html).

A large fairy ring of redwood trees is the location of a picnic ground in front of Welch-Hurst House. The building is made of native sandstone from the Vaqueros and San Lorenzo formations. Note the large round concretions used as monument caps near the front door of the house. Concretions are abundant in the San Lorenzo Formation. Also note the large prehistoric mortar hole carved in the large sandstone slab incorporated into the front right side of the path leading to the front of the house. Other mortar holes used for grinding acorns and other food products by Native Americans are present in several of the large boulders along a short trail behind the hostel building.

Continue around the left (west) side of the Hostel building. Follow the stairs or path down to the low flat area next to the building that is currently used as a volleyball court. Note that the Hostel building is built on a low straight ridge covered with blocky alluvium. The building is situated on an old terrace of Todd Creek just west of the trace of the fault. The low flat area occupied by the volleyball court represents an old stream meander of Todd Creek after being captured in its current drainage configuration, but before the incision of the modern gorge north of the Welch-Hurst House.

Continue west across the flat area and follow the old road downhill (to the west).

Stop I is located at a bridge over Todd Creek. Todd Creek has a steep drainage profile relative to Sanborn Creek. The creek has rapidly carved downward into the older alluvial fan deposits that once filled this portion of the San Andreas Rift Valley to a relatively higher level than exists today. Note the size of the large boulders in the creek and exposed in the steep hillsides along the creek and the road (fig. 6-13). These blocks are not bedrock, but rather, are materials that moved down the slope by mass movement in the past (landslides, rockfalls, debris flows, creep). Some of the large boulders near the bridge contain concretions.

Continue west along the trail for a couple hundred feet to the next stop.

Stop J is located near a precipitous drop off where a landslide has taken away part of the old road. The poorly consolidated sediments of the alluvial fan are prone to landslides in areas of steep stream incision. Use caution when approaching the escarpment! From the trail above the slump escarpment it is possible to see the layered beds of alluvial sediments. Note the tree roots exposed in the surface soil profile. The lack of trees in the landslide area reflects that much of this hillside fell away in a massive landslide event that happened during the particularly wet winter of 1995. Also note that very little sediment remains in the toe area of the landslide. Much of the landslide material probably moved downstream in the form of a debris flow. Numerous other slumps and landslides occur throughout the hillsides in this vicinity.

Return along the old road (trail) to the intersection with the paved road. Bear to the right, and then bear to the left past the gate onto the route of the San Andreas Trail. Follow this trail back to the vicinity of the Park Maintenance Building near Stop 8 on the Sanborn Nature Trail.

Along the San Andreas Trail look for landscape features that might display evidence of faulting and stream offset. The San Andreas Fault Zone is complex; in many places it is represented by multiple parallel and interconnecting faults. The landscape features, including linear scarps and the sag ponds, suggest that there may be several active fault traces within the vicinity. Note that although the landscape has been heavily modified by recent human activity, it still reflects the geomorphic profile of an alluvial fan, similar to the area near the RV campground area. It is likely that these flat areas were once aligned but have since been offset by movement along the fault.

Figure 6-13. Colluvium (boulders and soil) partly held in place by tree roots along the trail by Todd Creek near Stop I. The colluvium is derived from older alluvial deposits that are being exhumed by erosion along the eastern flank of Castle Rock Ridge.

Sanborn Nature Trail (continued)

The San Andreas Trail descends off an elevated portion of the alluvial terrace and follows a small stream down hill to an intersection with the Nature Trail near Stop E. Turn right on the Nature Trail (south toward Park Headquarters). Bear to the right and continue along the Nature Trail to Stop 9. Note that the trail follows the trace of the San Andreas Fault southward. Note the sag area along the trail on the right (the sag area is typically dry in the summer).

Stop 9 is near what appears to be an abandoned stream cut through the shutter ridge along the San Andreas Fault on the east side of the trail. At Stop 9, the Sanborn Nature Trail guide discusses how the leaves, flowers, and fruit of the California buckeye are poisonous to humans and animals. However, buckeye nuts were prepared as food by the Ohlone Indians when acorn supplies were low. Buckeye nuts are rich in starch, but are not suitable for food because they contain a poisonous glucoside, aesculin, which can cause severe gastroenteritis, depression, hyperexcitability, dilated pupils, and coma. The Native Americans roasted the nuts among hot stones, peeled and mashed them, and leached them with water for several days. This treatment apparently removed the toxic aesculin. Buckeyes can be particularly hazardous to pets (especially to dogs that chew sticks of buckeye wood).

Stop 10 is located near another gap in the shutter ridge. This one, however, looks like it was modified by human activity. Stop 10 provides an opportunity to examine the curved trunks of trees along the deflected stream drainage. The trees are adjusting to the slow creep of surface materials down the slope into the creek bed. Just south of the trees with curved trunks the stream curves to the left and cuts through the shutter ridge (fig. 6-14). The Nature Trail crosses a small bridge and then bears to the left at a trail intersection.

Stop 11 in the Sanborn Nature Trail guide is a location to examine a Pacific madrone tree. Unfortunately, the specimen to be examined is now dead, but there are many others in the vicinity. Madrone trees have a multitude of uses. The fruit (berries) are an important food source for many species of mammals and birds. The Ohlone Indians ate the berries both raw and cooked. Early European settlers preferred to use charcoal derived from madrone wood in the manufacture of gunpowder. Both Native Americans and early settlers used tea brewed from its bark, leaves, and roots of the madrone tree as relief for stomachaches and treatment for colds; this tea was also used topically as an astringent (useful against inflammation and to stop bleeding). Today, madrone is primarily used as an evergreen ornamental plant. Its hard wood resembles black cherry and is used as furniture paneling, flooring, tobacco pipes, and other novelties, in addition to firewood.

Stop 12 is a large boulder (locally called "Ghost Rock") along the Sanborn Nature Trail that displays tafoni-style weathering (fig. 6-15). Tafoni forms on rocks exposed at the surface for long periods of time, such as these boulders resting on an old surface of the alluvial fan. When precipitation soaks into porous sandstone, some of the mineral cement dissolves. As the rock dries out, capillary action brings moisture along with dissolved minerals to the surface. As the water evaporates, the minerals precipitate. In this manner, the rocks actually break down from the inside out as this weathering process removes the mineral cement below the surface. The wind and rain help to sculpt away the softer rock, leaving the more resistant, tightly cemented surface rock behind. Tafoni-style weathering is responsible for the unusual character of the massive Vaqueros Sandstone outcrops in Castle Rock State Park on the ridge west and above Sanborn County Park and along Skyline Boulevard. Local legend is that Ghost Rock may have

Figure 6-14. View along the Nature Trail between Stops 10 and 11. A small stream channel follows the trace of the San Andreas Fault before it cuts through the shutter ridge on the east side of the fault. Note the curved trunks of the large Ponderosa pines in the distance near a small bridge over the creek. The trees in the foreground are redwoods.

Figure 6-15. "Ghost Rock" is located at Stop 12 along the Nature Trail. The "mouth" is a typical example of taphoni-style weathering. The two "eyes" may be Native American grinding mortar holes in a rock that was later set upright into its current position.

been set up to appear as it does. The two "eyes" look similar to small grinding mortars elsewhere in the park area.

Stop 13 in the Sanborn Nature Trail guide describes the dusky-footed woodrat, a common pack rat in woodland and chaparral habitats throughout California. Woodrats gather litter from the forest floor to build small lean-to-style middens, typically under brush or in the pockets of tree stumps. Woodrats will gather whatever catches their eye, including garbage, and incorporate it into their middens.

The hiking trail ends near restrooms near the Park Office area and lower parking area. Additional stops at local winery and vineyards that provide views of the San Andreas Rift Valley in the vicinity of Sanborn County Park are described below.

Alternate Stop—Savannah-Chanelle Winery and Vineyards

Stop highlights: San Andreas Fault, shutter ridge, sidehill bench

The driveway and parking associated with the winery area and the tasting room are built right within the San Andreas Fault Zone, and geomorphic features associated with active faulting are well developed (fig. 6-16). A good view of the grounds is possible from a picnic area a shorth walk uphill from the parking area. This vista point provides a view along the trace of the fault to the south toward Sanborn County Park.

Figure 6-16. The Savannah-Chanelle Vineyards straddles the San Andreas Fault north of Sanborn County Park. The fault line passes through the parking area at the wine tasting room. The yellow dashed line in this image shows the approximate location of the fault and arrows show relative movement. This view is looking southeast from the winery's picnic area across the trace of the fault and the valley of Sanborn Creek (within the San Andreas Rift Valley). The mixed redwood and Douglas fir forest on the right is along McElroy Creek. McElroy Creek drains off of Castle Rock Ridge and displays displacement by stream capture where it crosses the fault near the vineyard. The grape vineyards in the foreground on the left are on a shutter ridge on the east side of the fault. The Cinnabar Vineyards are on El Soreno Ridge in the distance on the east side of the San Andreas Rift Valley.

This is a privately owned business, open to the public during business hours (11 am to 5 pm daily). From Sanborn park return north along Sanborn Road to Highway 9 and turn left (south). The driveway to the winery is on the left about 0.7 mile (1.2 km) south of Sanborn Road. Turn into the vineyards and proceed to the parking area in front of the tasting room.

The San Andreas Fault crosses Highway 9 near the driveway to the Savannah-Chanelle Winery and Vineyards (see fig. 6-1). The large home near the tasting room building was built on top of a shutter ridge associated with the fault. The trace of the fault follows a hillside bench along Sanborn Creek Valley along the lower eastern flank of Castle Rock Ridge (to the west). The bedrock in the hills consists of Eocene and Oligocene age marine sandstone and shale, whereas Quaternary alluvial-fan deposits underlie the bench and lowlands in the valley along Sanborn Creek. Rocks of Mesozoic age underlie the forests on El Sereno Ridge on the opposite side of the valley (east of the San Andreas Fault).

Alternate Stop—Cinnabar Vineyards and Winery

Stop highlights: San Andreas Fault, rift valley, vegetation contrast, offset streams

This stop provides excellent views of the San Andreas Rift Valley to the west and to the Santa Clara Valley to the east. Cinnabar Vineyards and Winery is located on the north end of El Sereno Ridge on the east side of the San Andreas Rift Valley near Sanborn County Park. This is a privately owned business that is open to the public only for special events. However, special arrangements can be made for groups to visit. The driveway leading to the mountaintop winery begins on Highway 9 about 2.5 miles (4 km) south of downtown Saratoga (see fig. 6-1). Be very careful driving up to the mountaintop in that the narrow single-lane road is locally very steep and winding.

The mountaintop setting provides spectacular views of Santa Clara Valley around San Jose to the east and the rift valley and Castle Rock Ridge to the west (fig. 6-17). Unobstructed views extend to the south where the San Andreas Fault passes beneath Lake Ranch Reservoir in the saddle between upper Sanborn Creek Valley and Lyndon Creek Valley (see chapter 5). The fault zone near Walden West and the Savannah-Chanelle Vineyards are clearly visible. To the north, a stark vegetation contrast highlights the difference of soil, bedrock, and climate conditions on opposite sides of the rift valley in the vicinity of Saratoga Gap where the San Andreas Fault crosses a low saddle between the Saratoga Creek and upper Steven Creek drainages.

It should be noted that despite the name Cinnabar there are no mercury mines or ore deposits associated with the vineyard, even though North America's largest historical mercury mining district is located only a few miles south in the New Almaden region of the eastern foothills of the Santa Cruz Mountains.

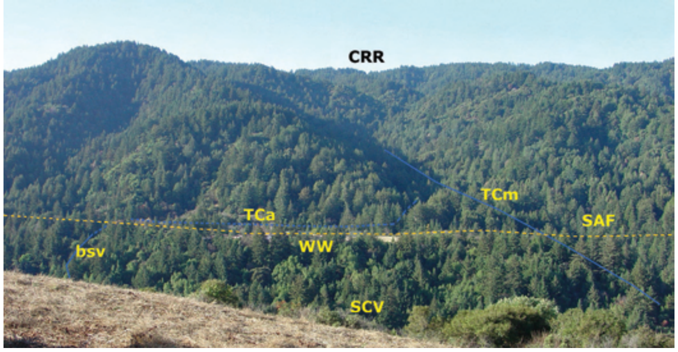


Figure 6-17. This view from the Cinnabar Winery shows part of the rift valley of the San Andreas Fault at Sanborn County Park. Open fields around Walden West (WW) are on a low shutter ridge on the east side of the San Andreas Fault (SAF). The modern drainage of Todd Creek (TCm) drains down a steep canyon off of Castle Rock Ridge (CRR). In the past, Todd Creek (TCa) used to flow south before cutting through the shutter ridge at Walden West before draining into Sanborn Creek Valley (SCV). The driveway leading to Walden West follows the beheaded-stream valley (bsv) of ancestral Todd Creek.

Alternate Stop—The Mountain Winery

Stop highlights: Vistas of the San Andreas Rift Valley, southern San Francisco Bay, Berrocal Fault

This stop provides vistas of the San Andreas Rift Valley in the vicinity of Sanborn County Park and unobstructed views of the entire South Bay region. The Mountain Winery is located on Pierce Road off of Highway 9 (Congress Springs Road) about 2 miles (3 km) south of downtown Saratoga (see fig. 6-1). From Highway 9, proceed uphill (to the west) about 0.2 miles (0.3 km) and the gated entrance to the Mountain Winery grounds is on the left. Unfortunately, the lower gates to the winery on are typically closed and access is limited to guests of events held at the facility or during open-air concerts which are scheduled from the late spring to early fall. It is worth inquiring in advance to see if the facility will be open to the public.

Paul Masson purchased a scenic mountaintop near Saratoga in 1901 and began clearing the land for vineyards and construction of what would become the historic Paul Masson Winery building. The Great San Francisco Earthquake of 1906 caused considerable damage to the new winery and widespread destruction throughout the communities in the South Bay. Paul Masson salvaged a 12th century Spanish front portal from St. Patrick's Cathedral in San Jose that was destroyed in the 1906 earthquake. He incorporated the arched doorway into the rebuilt winery building (now part of the concert stage). During the Prohibition Era most wineries in California were closed, but Paul Masson's Mountain Winery survived with a permit for production of sacramental wines. The winery building became a California Registered Historic Landmark and was placed on the National Registry of Historic Places in 1960. The mountaintop setting of the facilities provides spectacular views of the surrounding region including unrivaled sunset and evening views of the South Bay region.

The mountaintop setting of the Mountain Winery provides views to the west of the San Andreas Rift Valley around Sanborn County Park (fig. 6-18). The view looking west from the lower parking area of the Mountain Winery provides a good orientation to the vicinity of the Earthquake Hike route in Sanborn County Park described above. The geomorphology associated with the east side of the San Andreas Fault is highlighted by the vineyards of the Savannah Chanelle Winery and the grass-covered fields around Walden West School. The upland drainages of Sanborn and Todd Creeks are also visible on the steep, forested, eastern escarpment of Skyline Ridge.

The view looking to the east from both the lower parking area and the Mountain Winery's patio dining area encompasses the South Bay region, including the nearby eastern foothills to the Santa Cruz Mountains near Saratoga. A straight valley and adjacent ridge roughly 0.6 mile (1 km) east of the Mountain Winery follows the trace of the Berrocal Fault (see figs. 6-4 and 6-5). A thrust fault system known as the Range Front Fault (or Monte Vista Fault) runs along the base of the foothills near Interstate 280 and California Highway 85 in Saratoga. These faults are part of the San Andreas Fault system and may actually merge with the main fault zone at depth. Both the Berrocal and the Range Front Fault systems are considered to be potential earthquake-generating faults. The foothills around Saratoga are structurally complex, having numerous faults and folds that cut both older bedrock and younger, overlying alluvial sediments.

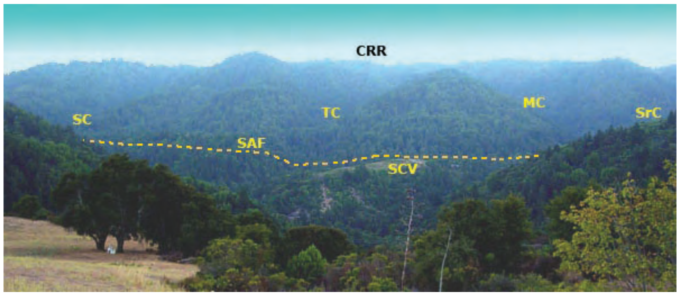


Figure 6-18. This view is looking west from the Mountain Winery parking area toward Castle Rock Ridge (CRR) and the rift valley of the San Andreas Fault (SAF). The Savannah-Chanelle Vineyards (SCV) is near the center of the image. On the east flank of the ridge, McElroy Creek (MC) drainage is to the right of the vineyard. Todd Creek (TC) is to the left of center, and Sanborn Creek (SC) is to the far left (south). Saratoga Creek (SrC) comes in from the upper right and drains to the lower left.

Note: Special thanks to James S. Moore (Eagle Scout, Boy Scouts of America, Skyline Council, Troop 5, Palo Alto, California), Tom Borra (Sanborn County Park Ranger, County of Santa Clara, Environmental Resources Agency, Los Gatos, California), and Carol Prentice (U.S. Geological Survey, Earthquake Hazards Team) for their help in developing this field trip.

Selected References

Alden, P., and Heath, F., 1998, National Audubon Society field guide to California: New York: Chanticleer Press, 477 p.

Brabb, E.E., Graymer, R.W., and Jones, D.L., 2000, Geologic map and map database of the Palo Alto 30' x 60' Quadrangle, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-2332, 2 sheets, scale 1:100,000 [http://pubs.usgs.gov/mf/2000/mf-2332/].

Brown, R.D., Jr., 1990, Quaternary Deformation, *in* Wallace, R.E., ed., The San Andreas Fault system, California: U.S. Geological Survey Professional Paper 1515, p. 83-113.

Bürgmann, R., Arrowsmith, R., Dumitru, T., and McLaughlin R., 1994, Rise and fall of the southern Santa Cruz Mountains, California, from fission tracts, geomorphology, and geodesy: Journal of Geophysical Research, v. 99, no. B10, p. 20181-20202.

Dickinson, W.R, Tectonic implications of Cenozoic volcanism in coastal California: Geological Society of America Bulletin, v. 109, no. 8, p. 936-954.

Elder, W., 2001, Geology of the Golden Gate Headlands, *in* Stoffer, P.W. and Gordon, L.C., eds., Geology and natural history of the San Francisco Bay Area—a field-trip guidebook: U.S. Geological Survey Bulletin 2188, p. 61-86 [http://geopubs.wr.usgs.gov/bulletin/b2188/].

Gilbert, G.K, Humphrey, R.L., Sewell, J.S., and Soul J.F., 1907, The San Francisco earthquake and fire of April 18, 1906, and their effects on structures and structural materials: U.S. Geological Survey Bulletin 324, 170 p.

Graymer, R.W., Sarna-Wojcicki, A.M., Walker, J.P., McLaughlin, R.J., and Fleck, R.J., 2002, Controls on timing and amount of right-lateral offset on the East Bay fault system, San Francisco Bay region, California: Geological Society of America Bulletin, v. 114, no. 12, p. 1471-1479.

Jachens, R.C., and Griscom, A., 2004, Geophysical and geologic setting of the earthquake, inferred from gravity and magnetic anomalies, *in* Wells, R.E., ed., The Loma Prieta, California, earthquake of October 17, 1989–geologic setting and crustal structure: U.S. Geological Survey Professional Paper 1550-E, p. E49-E80.

Lawson, A.C., chairman, 1908, The California earthquake of April 18, 1906; Report of the State Earthquake Investigation Commission: Carnegie Institution of Washington Publication 87, 2 vols.

McLaughlin, R.J., Langenheim, V.E., Schmidt, K.M., Jachens, R.C., Stanley, R.G., Jayko, A.S., McDougall, K.A., Tinsley, J.C, and Valin, Z.C., 1999, Neogene contraction between the San Andreas Fault and the Santa Clara Valley, San Francisco Bay region, California: International Geology Review, v. 41, p. 1-30.

McLaughlin, R.J., Clark, J.C., Brabb, E.E., Helley, E.J., and Colón, C.J., 2001, Geologic maps and structure sections of the southwestern Santa Clara Valley and southern Santa Cruz Mountains, Santa Clara and Santa Cruz Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map MF–2373, 5 sheets, scale 1:24,000 [http://geopubs.wr.usgs.gov/map-mf/mf2373/].

Page, R.A., Stauffer, P.H., Hendley, J.W. II, Donlin, C., Boore, S., Mayfield, S., and Diggles, M.F, 1989, Progress toward a safer future since the 1989 Loma Prieta earthquake: U.S. Geological Survey Fact Sheet 151-99 [http://pubs.usgs.gov/fs/1999/fs151-99/].

Prentice, C.S., and Schwartz, D.P, 1991, Re-evaluation of 1906 surface faulting, geomorphic expression, and seismic hazard along the San Andreas Fault in the southern Santa Cruz Mountains: Bulletin of the Seismological Society of America, v. 81, no. 5, p. 1424-1479.

Prentice, C.S., and Ponti, D.J., 1997, Coseismic deformation of the Wrights tunnel during the 1906 San Francisco earthquake—A key to understanding 1906 fault slip and 1989 surface ruptures in the southern Santa Cruz Mountains, California: Journal of Geophysical Research, v. 102, p.635-648.

Selby, M. J., 1993, Hillslope Materials and Processes: Oxford University Press, 466 p.

Wallace, R.E., 1990, The San Andreas Fault system, California: U.S. Geological Survey Professional Paper 1515, 283 p. [http://education.usgs.gov/california/pp1515].

7. Field Trip to the Skyline Ridge Area in the Central Santa Cruz Mountains

Trip highlights: San Andreas Fault scarps, sag ponds, vegetation and bedrock contrasts, regional vistas, Quaternary gravels, Tertiary marine rocks, ancient submarine landslide deposits, volcanic rocks (Mindego Basalt), Native American mortar holes in sandstone

This field-trip guide includes a collection of stops that may be selected to plan a geology field trip. The field-trip stops are along Highway 9 (Saratoga Road) and Highway 35 (Skyline Boulevard) between Castle Rock State Park and La Honda on Highway 84. Most stops are on lands maintained by the Midpeninsula Regional Open Space District. Outcrop and natural areas along the ridgeline crest of the Santa Cruz Mountains west of the San Andreas Fault are featured. Stops also include excursions to the fault itself in the Los Trancos and Monte Bello Open Space preserves. The inclusion of all stops listed below might be possible only with an early start and plans for a long day in the field. Stop descriptions below include information about interesting geologic features in the vicinity, but they may require additional hiking to visit (fig. 7-1).

Note that rattlesnakes can be encountered anywhere. Poison oak is prevalent, and ticks can be encountered any time of year, but mostly in the spring. The area is also mountain lion habitat. It is advisable to contact the Midpeninsula Open Space District before planning group visits to the preserves; maps and information are available on their website at http://www.openspace.org.

Geologic maps with descriptions of this region include Brabb and others (1997, 1998, and 2000). These maps are ideal for field-trip discussions. PDF format versions of the maps are available for downloading, plotting, or graphic modi-

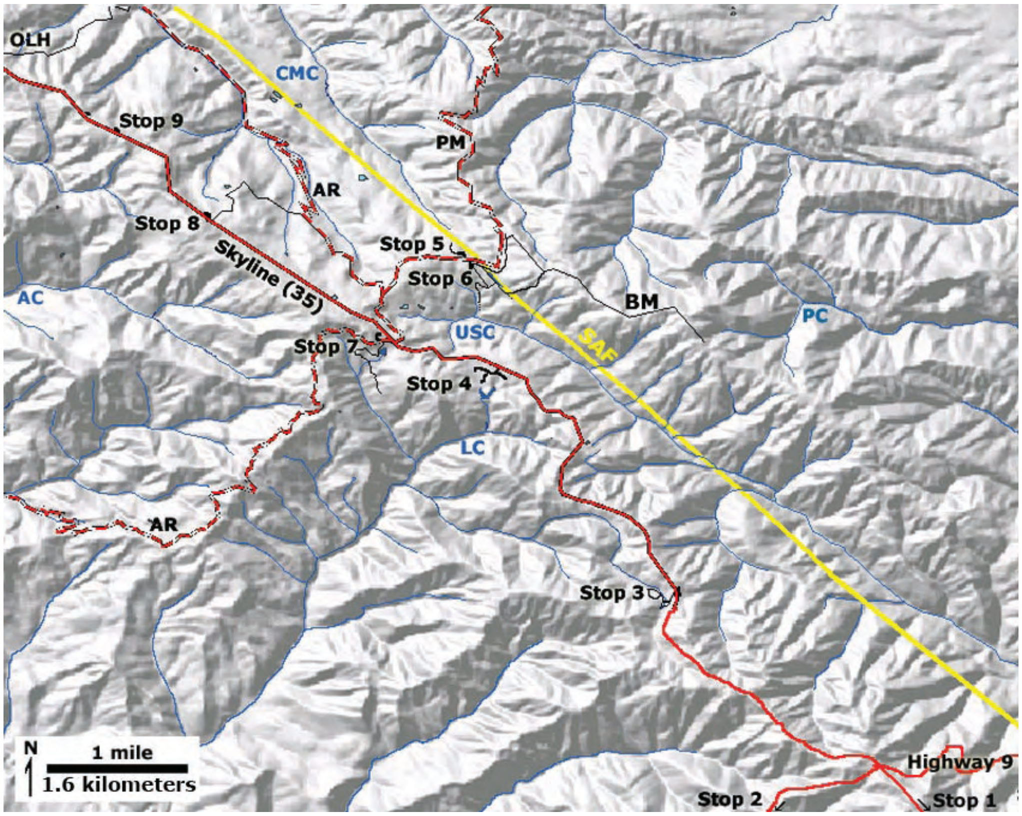


Figure 7-1. Map of the Skyline Ridge region of the north-central Santa Cruz Mountains along Highway 35 (Skyline Boulevard). The yellow line labeled SAF is the main trace of the San Andreas Fault. Stop 1 is at Castle Rock State Park. Stop 3 is a scenic overlook on Highway 9 west of Saratoga Gap. Stop 3 is the Long Ridge Open Space Preserve. Stop 4 is the Skyline Open Space Preserve. Stop 5 is the Los Trancos Open Space Preserve. Stop 6 is the Monte Bello Open Space Preserve. Stop 7 is the Russian Ridge Open Space Preserve. Stop 8 is a vista area near Clouds Rest. Stop 9 is Windy Hill Open Space Preserve. PM is Page Mill Road; AR is Alpine Road. BM is Black Mountain. Selected streams include Upper Stevens Creek (USC), Permanente Creek (PC), Corte Madera Creek (CMC), Lambert Creek (LC), and Alpine Creek (AC).

fication into handout at the *USGS San Francisco Bay Region Geology* website (http://sfgeo.wr.usgs.gov/).

The San Andreas Fault defines the boundary to two distinct geologic terranes in the north-central Santa Cruz Mountains. The east side of the San Andreas Fault is characterized by the Permanente Terrane, a belt of ancient oceanic crustal rocks (volcanic and sedimentary) of Cretaceous age that are part of the Franciscan Complex. The Permanente Terrane contains pillow basalt, sandstone, mudrocks, chert, and limestone in varying degrees of metamorphic grade, hydrothermal alteration, and structural shearing from both ancient and modern fault movement. Economic production of limestone is ongoing in the Permanente Creek area on the southeastern flank of Black Mountain in this field-trip area. The mine in the Permanente Creek area is about 2 miles directly east of Stop 6 (shown on fig. 7-1).

West of the San Andreas Fault is the Santa Cruz Mountain Block, a complex terrane composed of granitic and mafic igneous basement rocks that have intruded older Paleozoic and Mesozoic metamorphic rocks. These rocks are collectively called Salinian Complex. Salinian rocks are exposed to the southwest on Ben Lomond Mountain and in the north on Montara Mountain. In the Ben Lomond Mountain area, marble was historically mined for lime, and hard-rock aggregate is still actively mined. These crystalline basement rocks are overlain by a thick blanket of latest Cretaceous to late Tertiary sedimentary rocks and some basaltic volcanic rocks. In southern San Mateo and northern Santa Cruz counties this complexly faulted and folded sequence of sedimentary rocks is as much as 13,000 feet (4,000 m) thick and consists of rocks of Eocene, Oligocene, and Miocene age. Miocene-age volcanic rocks (Mindego Basalt) also occur in the Santa Cruz Mountain Block. These rocks of the Santa Cruz Mountains Block are bounded on the east by the San Andreas and Pilarcitos Faults and to the west by the San Gregorio Fault (rocks west of the San Gregorio Fault are part of the Pigeon Point Block). Oil production in the Half Moon Bay area was some of the first in California. Today, there is no active oil production in the region, however, some unrecovered oil (albeit small) may exist, as is suggested by a number of oil seeps in the region, perhaps most noteworthy being seeps along Tarwater Creek, a tributary in the greater Pescadero-Alpine Creek drainage area west of Skyline Ridge.

Page Mill Road generally defines the boundary between the Peninsula segment of the San Andreas Fault to the north and the Santa Cruz Mountains segment to the south. The Peninsula segment extends northward of Page Mill Road to offshore of San Francisco. It is characterized by very little seismicity since the massive magnitude 7.9 1906 San Francisco earthquake ruptured this section of the fault. The Peninsula segment also experienced an estimated magnitude 7.0 earthquake in 1838. Studies of offset alluvial fan deposits near San Andreas Reservoir suggest other major seismic events occurred at 1,810±50 years BP (before present) and 2,790±60 years BP as indicated by carbon 14 ages (Prentice and others, 1991). The average recurrence interval of major earthquakes on the Peninsula segment is estimated to be about 225 years. However, it must be stressed that earthquakes do not occur at regular preset intervals. Hall and others (1999) report an estimated overall slip rate of 17±4 mm/year for the Peninsula section, but the fault is currently displaying locked behavior. The modern Peninsula section of the San Andreas Fault runs parallel to, or slightly orthogonal to, the Pilarcitos Fault, which is an inactive ancestral strand of the San Andreas Fault. Although more than 185 miles (300 km) of offset is estimated for the San Andreas Fault in the San Francisco Bay region, only about 16 miles (26 km) of offset is accommodated by the modern Peninsula segment of the San Andreas Fault as determined by the offset of a belt of Cretaceous limestone within the Permanente Terrane of the Franciscan Complex (Griscom and Jachens, 1989). The rest of the offset occurred along the Pilarcitos Fault and other faults in the region.

In contrast to the Peninsula segment, the more seismically active Santa Cruz Mountains segment, which extends southward from Page Mill Road to the San Juan Bautista area, has experienced nearly a dozen magnitude 4 to 5 range earthquakes in the two decades proceeding the magnitude 6.9 1989 Loma Prieta earthquake. This seismicity shows that the plane of the San Andreas Fault dips at a steep angle approaching 75 degrees toward the west in the Santa Cruz Mountains.

Road Log to the Skyline Ridge Region of the Central Santa Cruz Mountains

Distance	Description
0.0 mi (0.0 km)	Intersection of Saratoga Road with Highway 85.
1.7 mi (2.7 km)	Intersection of Saratoga Road with Saratoga-Sunnyvale Road and Saratoga-Los Gatos Avenue (Highway 9) at downtown Saratoga. Proceed south on Highway 9 through downtown Saratoga.
3.5 mi (5.6 km)	The Mountain Winery is to the right (uphill about 1.2 miles to the parking area). The Mountain Winery was originally the Paul Masson Winery. The old Paul Masson Winery building is now the back stage area for a 1,000 seat outdoor concert facility and party grounds. The grounds of the winery provide exceptional views of the South Bay region. The hilltop facility is built on a ridge between linear valleys defined by the Berrocal Fault to the east and the San Andreas Fault to the west.
4.2 mi (6.7 km)	Bridge over Sanborn Creek. Sanborn Road (to Sanborn Park) is on the left.
5.0 mi (8.0 km)	Savannah-Chanelle Vineyards is on the left. Highway 9 crosses the San Andreas Fault in this vicinity (it is not apparent along the road due to plant and colluvial cover).
9.0 mi (14.5 km) **0.0 mi (0.0 km)**	Intersection of Highway 9 and Skyline Boulevard (Highway 35) at Saratoga Gap. Proceed south on Highway 9. **Reset the odometer mileage to zero**. Saratoga Gap Vista Area is a convenient gathering area at the intersections of Highway 9 and 35. Although the area is frequently patrolled, take things of value with you.
2.6 mi (4.2 km)	**Stop 1—Castle Rock State Park** (see stop description below). Restrooms are available here, albeit primitive. After the stop, return north to Highway 35 at Saratoga Gap.
0.0 mi (0.0 km)	Intersection of Highway 35 northwest of Highway 9 at Saratoga Gap; **Reset the odometer mileage to zero** at the intersection.
1.7 mi (2.7 km)	**Stop 2—Highway 9 Vista Point at Castle Rock State Park** (see stop description below). The overlook is on the left (east) side of the road. A restroom is available at this stop. After the stop, return north to Highway 35 at Saratoga Gap.
0.0 mi (0.0 km)	Intersection of Highway 35 northwest of Highway 9 at Saratoga Gap; **Reset the odometer mileage to zero** at the intersection.
0.7 mi (1.3 km)	Saratoga Summit Fire Station is on the left.
1.3 mi (2.1 km)	**Stop 3—Long Ridge Open Space Preserve** (see stop description below). After the stop continue north on Highway 35.
5.4 mi (8.7 km)	**Stop 4—Skyline Ridge Open Space Preserve** (see stop description below).
6.3 mi (10.1 km)	Intersection of Skyline Boulevard (35) with Page Mill Road and Alpine Road. Turn right on Page Mill Road.
7.6 mi (12.2 km)	**Stop 5—Los Trancos Open Space Preserve** (see stop description below). A restroom is available at this stop. Continue to the Monte Bello Preserve across Page Mill Road.

Continued.

7.7 mi (12.3 km)	**Stop 6—Monte Bello Open Space Preserve** (see stop description below). A restroom is available at this stop. Return to the intersection of Page Mill and Highway 35. The parking area to the Russian Ridge Open Space Preserve is just across Highway 35 on Alpine Road.
8.9 mi (14.3 km)	**Stop 7—Russian Ridge Open Space Preserve** (see stop description below). A restroom is available at this stop.
0.0 mi (0.0 km)	Return to the intersection of Alpine Road and Highway 35. Turn left (north) on Skyline Boulevard. **Reset the odometer mileage to zero**.
1.1 mi (1.8 km)	**Stop 8—Vista Point along Skyline Boulevard** (see stop description below). After this stop continue north on Highway 35.
4.8 mi (7.7 km)	**Stop 9—Windy Hill Open Space Preserve** (see stop description below). A restroom is available at this stop. **End of field trip**. **For location reference only:** north-bound travelers will find the intersection of Skyline Boulevard with La Honda Road (Highway 84) 2.2 miles north of the Windy Gap Open Space Preserve. Highway 84 connects between I-280 at Woodside and Highway 1 along the coast at San Gregorio State Beach. Alice's Restaurant is at located the intersection of Skyline Boulevard and Highway 84. Highway 84 provides a better return route to Highway 280 than the narrow, steep, and winding Page Mill Road.

Stop 1—Castle Rock State Park

Stop highlights: Massive Tertiary marine sandstone outcrops, tafoni-style weathering, vistas along Castle Rock Ridge

East of Highway 9, Skyline Boulevard follows Castle Rock Ridge; home of Castle Rock State Park. Castle Rock State Park is most famous for its massive outcrops of arkosic (feldspar-rich, lithic-poor) sandstone (lower to middle Eocene age). The Butano Sandstone forms the ridgeline of Castle Rock Ridge and much of Skyline Ridge and other ridges in the Santa Cruz Mountains west of the San Andreas Fault. The Butano Sandstone Formation contains as much as 10,000 feet (3,000 m) of marine rocks that are mostly sandstone but that also include interbedded shale and conglomerate.

It is advisable to call the park office in advance of a field trip to ensure that there is no conflict with other scheduled events and to inquire about park access fees for educational field trips. Parking within the State park lot requires a day use fee. Along the road parking is free; however, it can be quite limited on weekends and holidays.

The shortest route to see massive outcrops of Butano Sandstone is a 0.1 mile (0.2 km) trail to Indian Rock on the east side of the road. Indian Rock provides a view of Sanborn Creek Valley (along the San Andreas Fault). Be aware that the sandstone is slippery when wet and climbing on the rocks without appropriate equipment can be hazardous!

Slightly longer hikes include an uphill, about 0.3 mile (0.5 km) walk to Castle Rock itself. The trail starts in the main parking area. Castle Rock also displays spectacular cave-like tafoni weathering. Goat Rock Overlook along the Ridge Trail provides spectacular views of the San Lorenzo River Valley to the west. Goat Rock is perhaps the highest cliff in the park (about 200 feet or 65 meters) and involves a more strenuous hike of about 1 mile (1.6 km). In addition, Castle Rock Falls overlook is worth the detour from the Ridge Trail.

Note the tafoni-style weathering of the sandstone (fig. 7-2). Tafoni forms from differential weathering of sandstone over time. Precipitation soaks into the sandstone and dissolves mineral cements that then migrate to the rock surface as the rock dries. This produces a hardened patina crust on rock surfaces. The sand that has lost its cement inside the rock easily

Figure 7-2. Goat Rock is a popular hiking destination in Castle Rock State Park. It is deeply pocketed by tafoni-style weathering.

crumbles when exposed, resulting in the cave-like holes in the sandstone.

Stop 2—Highway 9 Vista Point

Stop highlights: Vista of the Monterey Bay region, Ben Lomond Mountain (a fault-bounded block of Salinian basement)

The vista point is located 1.8 miles south of the intersection of highways 9 and 35 at Saratoga Gap. The stop provides views south and west of Castle Rock Ridge toward the southwestern Santa Cruz Mountains and the drainage basin of the San Lorenzo River (fig. 7-3). Distant views on a clear day include Monterey Peninsula and Monterey Bay. The valley of the San Lorenzo River is underlain by a complexly folded and faulted sequence of marine sedimentary rocks, mostly shale, of Eocene, Oligocene, and Miocene age. To the west is Ben Lomond Mountain, a massive block of Salinian crystalline basement rock overlain by a discontinuous cover of late Tertiary sedimentary rocks that are bounded on the northeast by the Ben Lomond Fault. Closer by is the southern end of Butano Ridge, a ridge of resistant Butano Sandstone bounded on the northeast by the Butano Fault. Castle Rock Ridge along Highway 35 is also a ridge composed of Butano Sandstone bounded on the northeast by the San Andreas Fault. All three faults, and others in the San Lorenzo River Valley, display evidence of Quaternary offset and may be capable of producing earthquakes.

Figure 7-3. View looking southwest from the vista area along Highway 9, located 1.8 miles (3 km) south of Saratoga Gap. MB is Monterey Bay; BLM is Ben Lomond Mountain, and BR is Butano Ridge. The entire visible landscape is part of the San Lorenzo River basin. The valley is typically shrouded in fog in the morning hours.

The Skyline to the Sea Trail passes through the vista area. The uphill end of the trail begins at Saratoga Summit in Castle Rock State Park. The-18-mile long trail passes through Big Basin State Park and ends at Waddell Creek near Año Nuevo State Park along Highway 1 at the border between Santa Cruz and San Mateo Counties.

Stop 3—Long Ridge Open Space Preserve

Stop highlights: Tertiary sandstone outcrops, vista of fault-bounded Butano Ridge, oak and mixed evergreen forest

Long Ridge Open Space Preserve offers trails through grassland bald areas and mixed evergreen forests (consisting of moss-covered live oaks, bay laurels, madrone, and Douglas fir). A 0.25 mile (0.4 km) walk from the trail head leads to a rocky outcrop on the ridgeline consisting of Butano Sandstone of Eocene age (fig. 7-4). The view to the west encompasses the straight valley of Pescadero Creek where it follows the trace of the Butano Fault at the base of Butano Ridge. This region is the most extensive wilderness areas left in the Peninsula region and encompasses Portola, Pescadero Creek, and Butano State Parks. Although the region was heavily lumbered in the late 19th and early 20th centuries, many of the redwood groves are returning. Efforts are now underway to restore the Pescadero Creek salmon population.

From the parking area proceed west and then north on the main trail (Hickory Oaks Trail). Butano Sandstone outcrops can be seen on a foot trail that cuts off to the left near the top of the hill. Watch out for rattlesnakes and poison oak. An additional distraction is a walk through an amazing oak grove on a spur trail that leads to the left (south) a short distance from the trail head. About 10 vehicles can fit if parked closely along the roadside parking area on Highway 35. Additional space for 6 more vehicles are a short distance north along the road.

Stop 4—Skyline Ridge Open Space Preserve

Stop highlights: Ancient submarine landslide deposits (Lambert Shale), restored upland habitats

This stop involves a 0.6 mile (1 km) round-trip walk to Horseshoe Lake at the head of Lambert Creek (fig. 7-5). Upon entering the preserve, turn right and park in the northernmost parking area. A sign at the trail head says "Ridge Trail to Horseshoe Lake 0.3 mi."

The area along the road was once a Christmas tree farm (soon to be restored to its original oak woodlands and grasslands setting). Horseshoe Lake has a beautiful setting amongst mixed evergreen and Douglas fir forests. Bobcats are frequently seen here, and the area is mountain lion habitat. On warm days, the air around the pond can be crowded with dragonflies. A small trail next to a wooden bridge leads to the dam spillway and a small outcrop area of Lambert Shale (the destination of this field-trip stop). Be cautious handling rocks and plant material because scorpions, black-widow spiders, and poison oak are found here. Also note that the creekbed exposures may not be accessible during the wet winter season.

The Lambert Shale is of Oligocene to lower Miocene age and is about 4,800 feet (1,460 m) thick in the Santa Cruz Mountains. It only occurs west of the San Andreas Fault. The formation consists of dark-gray to pinkish-brown, moderately well cemented siliceous mudstone, claystone, and siltstone. Sandstone bodies as much as 100 feet (30 m) thick, glauconitic sandstone beds and microcrystalline dolomite are present

Figure 7-4. This view looking toward the northwest shows small outcrops of Butano Sandstone in a grassy "bald" area along Long Ridge. The valley of Pescadero Creek and Butano Ridge are in the distance.

Figure 7-5. View of Horseshoe Lake in the headwaters of Lambert Creek. A mixed evergreen and Douglas-fir forest grows on the cooler, wetter, north-facing slopes. Chaparral grows in the foreground on the drier south-facing slopes.

in places. The upper part of the section contains chert. In outcrop, it resembles the Santa Cruz Mudstone and parts of the Purisima Formation (exposed along the coast between Santa Cruz and Half Moon Bay); (Brabb and others, 2000).

This small outcrop at the dam spillway is a typical Lambert Shale outcrop in the Santa Cruz Mountains; there isn't much to see at first. However, closer inspection reveals curious features about this mudrock formation. Note the character of the small sandstone bodies in the outcrop area. The sandstone bodies have unusual shapes ranging from smooth and rounded to elongate or jagged. They suggest that the Lambert Shale accumulated, in part, as massive chaotic units, possibly as massive submarine landslide deposits. The siliceous nature also suggests deposition in offshore areas of upwelling marine currents where siliceous diatom blooms occurred.

Stop 5—Los Trancos Open Space Preserve

Stop highlights: Fault scarps, pull-apart basin with sag pond, view of the San Andreas Rift Valley, Pliocene- and Pleistocene-age alluvial gravels (Corte Madera facies)

Volunteers from Foothill College developed and maintain the San Andreas Fault Trail at Los Trancos Open Space Preserve. The trail follows the trace of the San Andreas Fault and associated slump escarpments throughout oak woodlands. Posts have been placed along the lines of ground rupture from the 1906 earthquake. A popular destination along the Los Trancos Fault Trail is a historic fence line offset by the strike-slip rupture of the fault has been restored to its original orientation; the original fence has long since deteriorated. Other features include trees that fell during the 1906 earthquake and have since regrown and scenic vistas along the trace of the San Andreas Fault (fig. 7-7). The Midpeninsula Open Space District provides a brochure for the San Andreas Fault Trail that describes nine stops along a 1.5 mile (2-4 km) hiking route (http://www.openspace.org/preserves/pr_los_trancos.asp). This field trip only utilizes hiking two stops from the San Andreas Fault Trail brochure.

Just to the north of the parking area in a chaparral-covered saddle between two hills. During wet periods water accumulates in a low area here. The saddle represents a small pull-apart basin (with sag pond). Low white-capped posts show the location of surface rupture caused by the 1906 earthquake. However, this is not considered the main trace of the San Andreas Fault. It is one of many areas throughout the Santa Cruz Mountains where intense earthquake shaking caused gravity driven ridge-crest spreading and slumping. The main trace of the San Andreas Fault is several hundred feet to the east of this location.

Hiking Stop One is located at an overlook a short distance beyond the trailhead at the west end of the Los Trancos parking area. This overlook provides a similar vista of the Upper Stevens Creek valley as the one described below at the Monte Bello Preserve. The overlook is along a section of trail lined with boulders of conglomerate containing clasts of volcanic rock (andesite porphyry, diorite, and gabbro) imbedded in a tightly cemented sandy matrix. These boulders were derived from Cretaceous-age conglomerates exposed along the Sierra Azul Ridge from Mount Umunhum and Loma Prieta Peak, nearly 23 miles (37 km) to the south (and visible on a clear day from this location). The poorly consolidated sandy gravel bearing the conglomeratic boulders are named the "Corte Madera facies" of the Santa Clara Formation, named after Corte Madera Creek, the drainage just north of this location along the San Andreas Fault. These poorly consolidated sediments are estimated to have been deposited roughly 2 million years ago on an alluvial fan draining from the Sierra Azul and Loma Prieta Peak summit region. Right-lateral movement of the fault has offset these materials from their sediment source area by a minimum distance of about 19 miles (30 km), providing an average long-term rate of offset at about 15 mm per year. These ancient deposits are preserved in a massive sliver-like trough within San Andreas Fault Zone that extends from Upper Stevens Creek Valley into the Corte Madera Creek drainage. The Corte Madera facies deposits are well drained and preferentially support grasslands and chaparral habitats in contrast to the surrounding rocks that host mixed evergreen forests and oak woodlands.

Hiking Stop Two is several hundred feet farther along the trail and is located at a monument in a grassy field with a spectacular view of the central San Francisco Bay region. This stop provides a view northward along the San Andreas Fault along the Corte Madera Creek drainage and onward to Crystal Springs Reservoir and San Andreas Lake, two reservoirs built in the San Andreas Rift Valley that can be seen from here on a clear day. The San Andreas Fault was named for a natural sag pond along the fault that was inundated by the construction of San Andreas Reservoir dam. This overlook provides an opportunity (on a clear day) to reflect on the setting and natural history of San Francisco Bay region.

On a clear day Mount Diablo, the East Bay Hills, and the Diablo Range are visible east of the bay. The Hayward Fault runs along the base of the western slope of the East Bay Hills. The bay itself floods an ancient valley system associated with the stream and river system that drains through the bay. During the climax of the last ice age about 18,000 years ago, sea level was as much as 400 feet (120 m) lower, and these river systems merged and flowed into a canyon that is now the Golden Gate.

Return to the parking area and cross the road to the parking lot for the Monte Bello Preserve to continue this walking excursion.

Figure 7-6. Boulders of conglomerate like this one are common along the trails near the parking area for Los Trancos and the Monte Bello Preserves. The conglomerate boulders consist of tightly cemented gravels dominated with clasts of andesite porphory and are part of the Corte Madera facies of the Santa Clara Formation, with an original source area in the Loma Prieta and Mount Umunhum summit region. The boulders are within alluvial deposits that filled a combination erosional and structural trough along the San Andreas Fault zone. These deposits are now exposed in a geographic high in a saddle between the Upper Stevens Creek and Corte Madera Creek drainages (see also figures 3-4 and 3-5).

Stop 6—Monte Bello Open Space Preserve

Stop highlights: Sag pond, fault scarps, vegetation and bedrock contrasts, Franciscan Complex, limestone, conglomerate

Hiking Stop One is at the trail head in the Monte Bello Preserve parking area. Maps of the preserve are on display. Blocks of locally derived serpentinite and conglomerate are around the trail head. The blocks are from the Corte Madera facies of the Santa Clara Formation. Vegetation contrasts in the Upper Stevens Creek Valley partially reveal that the Corte Madera facies fill a structural graben in the San Andreas Rift Valley. In the Monte Bello Preserve, the Corte Madera facies contains a interesting mix of rock types—cobbles and boulders of serpentinite, conglomerate, and mollusk-bearing marine sandstone can be found amongst the blocks and pieces of andesite porphyry-bearing conglomerate that dominate the deposit. These rocks are also well exposed nearby as blocks, boulders, and cobbles in the creekbed of Upper Stevens Creek. The fossils include turritellid gastropods, crepidula, clams, and other bivalves encased in coarse sandstone probably of Late Miocene age. The fossiliferous sandstone derived from an unknown source along the rift valley, possibly the upper Lambert Shale.

Figure 7-7. Trees like this oak along the San Andreas Fault Trail are a living reminder of the damage caused by the 1906 earthquake. Many older trees in both the Los Trancos and adjacent Monte Bello Open Space Preserve display damage from falling over or being broken during the earthquake.

Hiking Stop Two is at the intersection of two paths approximately 0.1 miles (0.2 km) south of the trailhead. This location provides an excellent view to the south along the straight valley of Stevens Creek with Mount Umunhum and Loma Prieta Peak in the distance (fig. 7-8). The trail to the right descends to Upper Stevens Creek (a good place to observe a mixture of rocks and bedrock exposures along the west side of the valley). A change in vegetation along the east side of this grassy area probably marks the boundary between the Santa Clara Formation gravels under the grasslands and the forest-covered Tertiary sedimentary formations that lie west of the San Andreas Fault (mostly Lambert Shale of Oligocene to Miocene age in this area). This vegetation boundary probably defines the trace of the Pilarcitos Fault, an ancient strand of the San Andreas Fault that splays off the current main strand of the San Andreas Fault at this point. The Pilarcitos Fault extends northward to the Rockaway Beach area on the San Mateo Coast before going offshore (see chapter 8). However, evidence of a fault in this area is not clear beyond a change in bedrock and vegetation. No fault plane is seen in the stream bed outcrops. In contrast, the active main trace of the San Andreas Fault is clearly visible on the east side of the valley where surficial offset, fresh fault scarps, and other features associated with the fault are obvious.

Four distinct plant communities reflect the underlying geology and soil conditions: mixed evergreen and oak woodlands and chaparral cover the ancient bedrock east of the San Andreas Fault on Black Mountain. Grasslands cover the alluvial gravels of the Santa Clara Formation under the central valley area, and Douglas fir forest covers the marine shale and sandstone that underlie Skyline Ridge on the west side of the fault valley.

Hiking Stop Three is along the San Andreas Fault. From the trail intersection follow the trail to the west through the old walnut orchard to the Monte Bello Road (trail). Monte Bello Road follows the escarpment of the 1906 rupture of the San Andreas Fault. The size and extent of this escarpment and associated sag pond that fills the fault zone here suggests this fault trace has been experiencing episodic earthquakes for

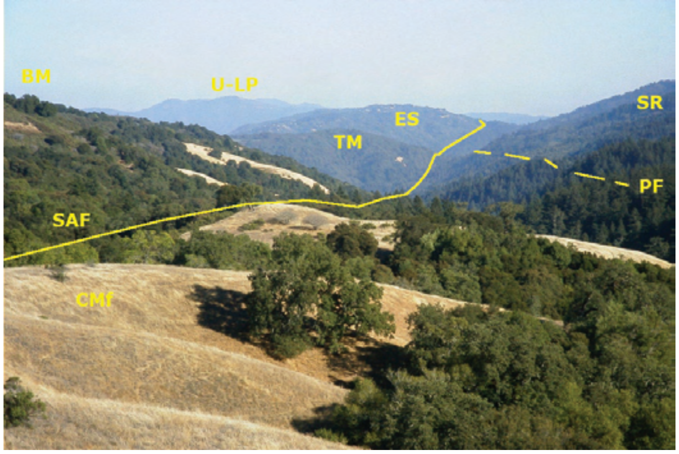


Figure 7-8. This view is looking southeast along the straight valley of Upper Stevens Creek that basically follows the trace of the San Andreas Fault (SAF). Black Mountain (BM) is on the left, and Skyline Ridge (SR) is on the right. Table Mountain (TM) and El Sereno Ridge (ES) near Saratoga Gap are in the middle of the image. The fault passes to the right (west) of the Mount Umunhum Loma Prieta summit area (U-LP) and in the distance. The conglomerate boulders in the Corte Madera facies gravels (CMf) that underlie the grasslands in this vicinity were derived from outcrops in the ancestral summit areas of those two mountains. The Pilarcitos Fault (PF) probably follows the drainage of Upper Stevens Creek on the right.

many thousands of years. It also implies that there is a vertical component to fault motion (hence the escarpment). Walk to the south along Monte Bello Road to a park bench adjacent to the sag pond and several large Bay Laurel trees (fig. 7-9). An interpretive plaque describes the succession of pond formation and filling along the fault. A large boulder of serpentinite is visible next to the shore of the pond a short distance south of the park bench. South of the Sag Pond the landscape along the fault zone displays an unusual topography, hinting of a series of fault-bounded grabens and horsts within the fault zone. About 0.8 mile (1.3 km) south of the sag pond is a small abandoned quarry in Franciscan limestone.

Hiking Stop Four is located near the intersection of Monte Bello Road (trail) and Page Mill Road. Return by the Monte Bello Road toward the parking area. The outcrop is near where the fault crosses Page Mill Road and is on the east side of the fault. This small outcrop consists of highly sheared greenstone (altered basaltic rock) with pods of dolomitic limestone. These are likely ancient pillow basalt (now sheared and altered) with calcareous marine ooze deposits (dolomitic limestone) of Early Cretaceous age. Massive limestone deposits on Black Mountain and the surrounding area are interpreted as ancient oceanic atoll deposits that were accreted onto the continental margin rather than being subducted during formation of the Franciscan Complex in the region east of the San Andreas Fault. Surficial weathering of these limestone deposits has produced an unusual karst landscape on the top of nearby Black Mountain (fig. 7-10).

Return to the parking area via the dirt path along the south side of Page Mill Road. Cobbles and boulders of conglomerate of the Corte Madera facies are exposed along the trail.

Stop 7—Russian Ridge Open Space Preserve

Stop highlights: Outcrops of Tertiary marine rocks (Vaqueros Sandstone and Lambert Shale), Native American grinding mortar holes, oak woodlands

Follow the Old Page Mill Trail to the spillway area of Alpine Lake about 0.1 mile (0.2 km) south of the Russian

Figure 7-9. Bay Laurels grow on an up-thrust escarpment of the San Andreas Fault next to a long, linear sag pond that fills the fault zone. This view is along the Monte Bello Road (trail).

Figure 7-10. These limestone outcrops on the top of Black Mountain display karst weathering. This limestone is mined in the Kaiser-Permanente (Stevens Creek) Quarry on the southeastern flank of Black Mountain.

Figure 7-11. These mortar holes made by prehistoric Native Americans are in a Vaqueros Sandstone outcrop along Alpine Creek below the dam at Alpine Lake.

Ridge Open Space parking area at the intersection of Alpine and Skyline roads. Below the dam is a massive outcrop of Vaqueros Sandstone (Oligocene to Early Miocene age, or roughly 30 to 20 million years old). Examine the outcrop to determine the orientation of the graded bedding of the sandstone and the structural strike and dip of the beds.

Oak woodlands and a perennial supply of water made this an attractive area to prehistoric people who carved many mortars (round holes) in the sandstone of natural stone ledge of a waterfall along the streambed below Alpine Lake (fig. 7-11). These ancient people probably used the mortars to grind and process acorns and other seeds harvested from the surrounding area.

Figure 7-12. Laminated beds in sandstone and shale in the Lambert Shale along the loop trail at Russian Ridge Open Space Preserve.

An optional loop walk of about 0.4 mile (0.7 km) is to continue west on Old Page Mill Trail and take a foot trail to the right that loops around to the main trail. This trail junction is less than 0.1 mile (0.2 km) west of the dam. This trail provides vistas of the redwood and mixed evergreen forests in the Alpine Creek drainage basin. The trail leads through mature oak woodlands and grass-covered slopes to an outcrop of interbedded sandstone and shale (fig. 7-12). This rock is part of the Lambert Shale, also of Oligocene to Early Miocene age, or roughly 30 to 20 million years old. Return via the Old Page Mill Trail to Alpine Lake. A visitor center next to the pond has nature exhibits, an interesting collection of stuffed animals, and at least one snake.

Stop 8—Vista Point along Skyline Boulevard (Highway 35)

Stop highlights: Vista of the San Francisco Bay region, boulders of Mindego Basalt, a soil profile

Near this vista parking area is a local road named Clouds Rest. The vista area provides a spectacular view of the mid-peninsula region of San Francisco Bay. On a clear day, visibility extends to Mount Diablo, the highest peak in the northern end of the Diablo Range in Contra Costa County. This area is frequently shrouded in morning fog, especially when a thick marine layer moves in from offshore. The entire Highway 35 passage through the Santa Cruz Mountains can become immersed in dense fog with miserable wet and windy conditions any time of year. It is best to avoid this high section of highway when these conditions persist.

The stop also provides an exposure of a thick soil profile in the cut on the opposite side of the road from the overlook parking area. Here, a thick blanket of colluvium bearing basaltic boulders overlies deeply weathered shale bedrock. The basalt is derived from local sources in the surrounding uplands. The Mindego Basalt and related volcanic rocks occur in the northern Santa Cruz Mountains. These basaltic rocks are both intrusive and extrusive and are of Oligocene and Miocene age. The Mindego Basalt has yielded a radiometric age of 20.2 (±1.2) million years (Brabb and others, 2002). The intrusive igneous rock is medium to coarsely crystalline and is dark greenish gray to orange brown. As in the vista point outcrop, the basalt commonly weathers spheroidally and crops out as tabular bodies intruding older sedimentary rocks. Minor amounts of sandstone and mudstone are also locally exposed in the road cut (fig. 7-13).

Stop 9—Windy Hill Open Space Preserve

Stop highlights: Vistas of the San Francisco Bay region, the San Mateo Coast, and the San Andreas Rift Valley

The grass covered hilltops along Highway 35 at Windy Hill Open Space Preserve provide unhindered observation of the northern Santa Cruz Mountains from the Pacific Ocean to San Francisco Bay and beyond. A short trail (about 0.2 mile) starts at the parking area and winds around the side and eventually to the top of the hill just to the north of the parking area. From here, the trace of the San Andreas Fault can be seen from the Monte Bello Preserve area northward to Crystal Springs Reservoir and beyond. Shale and sandstone of the San Lorenzo Formation and the Butano Sandstone underlie the grasslands and oak woodlands along this section of Skyline Boulevard (fig. 7-14).

Selected References

Brabb, E.E., Graham, S., Wentworth, C., Knifong, D., Graymer, R., and Blissenbach, J., 1997, Geologic map of Santa Cruz County, California, a digital database: U.S. Geological Survey Open-File Report 97-489, scale 1:62,500, 2 sheets [http://pubs.usgs.gov/of/1997/of97-489/].

Brabb, E.E., Graymer, R.W., and Jones, D.L., 1998, Geology of the onshore part of San Mateo County, California: U.S. Geological Survey Open-File Report 98-137, 1 sheet, scale 1:62,500 [pubs.usgs.gov/of/1998/of98-137/].

Brabb, E.E., Graymer, R.W., and Jones, D.L., 2000, Geologic map and map database of the Palo Alto 30' x 60' Quadrangle, California: U.S. Geological Survey, Miscellaneous Field Studies Map MF2332, 2 sheets, scale 1:100,000 [http://pubs.usgs.gov/mf/2000/mf-2332].

Griscom, A., and Jachens, R.C., 1989, Crustal and lithospheric structure from gravity and magnetic studies, *in* Wallace, R.E., ed., The San Andreas Fault system in California: U.S. Geological Survey Professional Paper 1515, p. 239-259 [http://education.usgs.gov/california/pp1515/].

Hall, N.T., Wright, R.H., and Clahan, K.B., 1999, Paleoseismic studies of the San Francisco Peninsula segment of the San Andreas Fault Zone near Woodside, California: Journal of Geophysical Research, v. 104, no. B10, p. 23215-23236.

Prentice, C.S., Miemi, T.N., Hall, T.N., 1991, Quaternary tectonic studies of the northern San Andreas Fault, San Francisco Peninsula, Point Reyes, and Point Arena, California [field-trip guidebook]: California Division of Mines and Geology Special Publication 109, p. 25-34.

Figure 7-13. A thick blanket of colluvium bearing spheroidally weathered boulders of basalt overlies deeply weathered shale bedrock at the Highway 35 vista point near Clouds Rest.

Figure 7-14. The San Andreas Fault follows the valley of Corte Madera Creek on the north side of Black Mountain (the high point in this image).

8. Field-Trip Guide to Faults and Geology in San Mateo County—Northern Santa Cruz Mountains and Along the Coast

Trip Highlights: San Andreas Fault along the I-280 and Skyline Boulevard corridor and at Mussel Rock Park; Calero Limestone at Rockaway State Beach; Devil's Slide; Montara Mountain granite; Seal Cove Fault; the San Gregorio Fault system; and geologic structures exposed along the coast at Montara State Beach, James V. Fitzgerald Marine Reserve, and at Pillar Point on Half Moon Bay

This field trip focuses on the geology in the northern Santa Cruz Mountains and the coast in San Mateo County. Selected stops highlight landscape features and bedrock along the San Andreas and San Gregorio Fault Zones and other localities that reveal information about the geologic evolution of the landscape. The field trip follows a loop route that begins near Crystal Springs Reservoir on I-280. The route follows I-280 and Highway 35 (Skyline Boulevard) north, then follows Highway 1 south along the San Mateo Coast before returning east on Highway 92 back to I-280.

Planning Your Field Trip

A field trip along the San Andreas Fault and to the coast in San Mateo County should be planned according to time limiting factors—tide conditions and trip destination interests. You will not want to attempt to visit coastal localities described in this guide during high tide or during inclement weather. The field trip described here starts at the Park and Ride at the

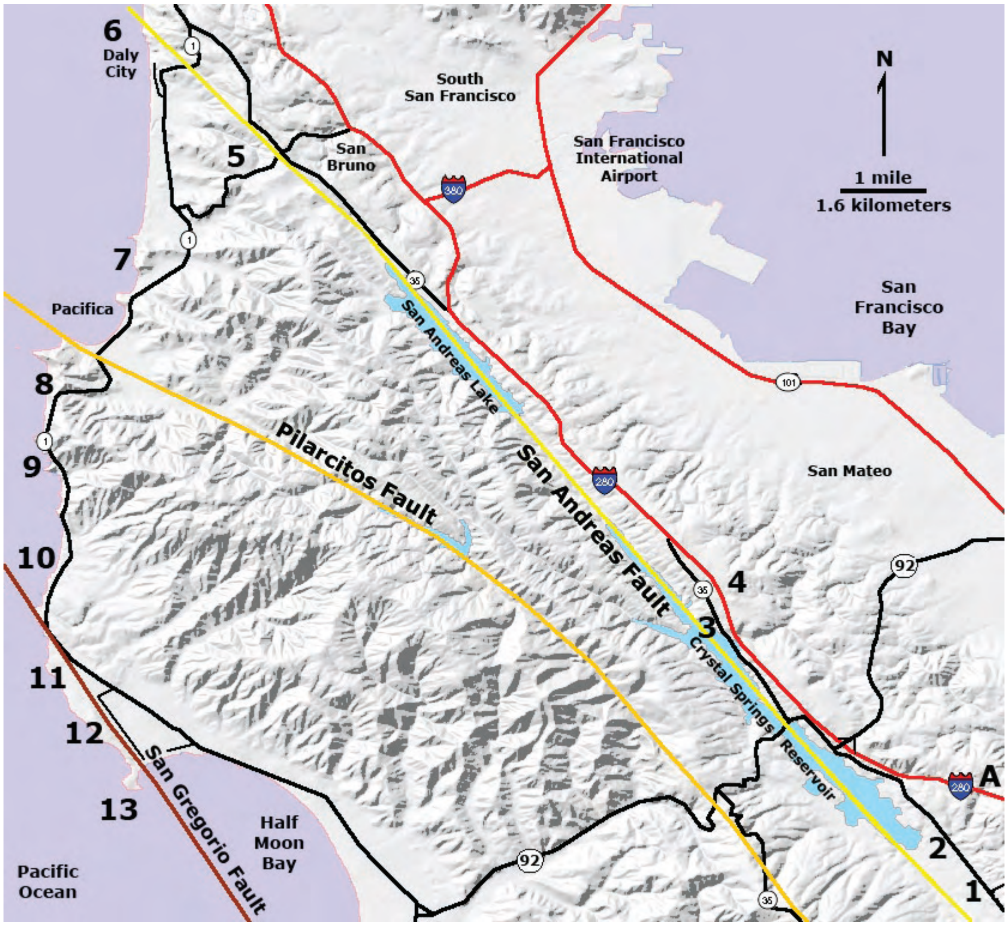


Figure 8-1. Map of the southern San Francisco Peninsula showing major faults in the northern Santa Cruz Mountains in San Mateo County. Stops include: (A) I-280 Vista Point, (1) Filoli Center, (2) Pulgas Water Temple, (3) Crystal Springs Dam, (4) I-280 Rest Area, (5) Milagro Ridge, (6) Mussel Rock Park, (7) Pacifica Quarry, (8) San Pedro Mountain and Devil's Slide, (9) Montara Mountain, (10) Montara Beach, (11) James V. Fitzgerald Marine Preserve, (12) Half Moon Bay Airport, and (13) Pillar Point and Mavericks.

Edgewood Road exit on I-280, where extra cars can be left during the field trip. **The road log presented below follows a recommended route for when low tide occurs in the mid afternoon.** Many websites provide tide information; search "tides" and "Half Moon Bay" on the World Wide Web to find a reasonable low-tide estimate for the coast. Also, be sure to check weather forecasts and projected wave heights. The San Mateo beaches and tide pool areas are extremely dangerous places during high surf. High waves can occur unexpectedly.

More stops are provided than could be reasonably visited in one day without rushing. Optional stops are included in this guide to help plan the best trip for specific group interests or time constraints. For instance, although the Filoli Center is a wonderful trip destination, it is both fairly expensive and a time consuming venture that requires advanced planning and should be considered for a separate trip. Groups in a hurry might consider at least one stop along I-280 for the first part of the trip. The recommended northbound route presented below includes the all-important restroom stop at the northbound I-280 Rest Area (Stop 4 described below).

If low tide occurs in the morning, plan to head directly to Half Moon Bay, but consider stopping first at the I-280 Vista Area (Optional Stop A) just north of the Edgewood Road exit before taking Highway 92 west. Be sure to take a detailed map of San Mateo County with you on the trip. Two other geology and engineering field trips in this region include Andersen and others (2001) and Williams (2001); Brabb and others (1998) provide a geologic map of the area.

Road Log to Northbound Trip: San Andreas Rift Valley and San Mateo Coast

Distance	Description
0.0 mi (0.0 km)	**Park and Ride** (east side of I-280 at Edgewood Road). This is a good location to carpool from (but do not leave valuables in cars). The Edgewood Road/Cañada Road exit on I-280 is located 4 miles (7 km) north of Woodside Road (Highway 84) and is 6 miles (10 km) south of the Highway 92 exit for Half Moon Bay. Drive west on Edgewood Road.
0.7 mi (1.1 km)	Turn right (north) on Cañada Road. Note that Cañada Road runs roughly parallel to the San Andreas Fault through its rift valley. Outcrops of Franciscan sandstone (graywacke), greenstone, and some serpentinite can be seen along the road and in bedrock exposures along the shoreline of Crystal Springs Reservoir.
2.0 mi (3.2 km)	**Stop 1—Filoli Center** (optional stop; see description below). Continue north on Cañada Road.
2.4 mi (3.9 km)	**Stop 2—Pulgas Water Temple** (optional stop; see description below). Continue north on Cañada Road.
4.7 mi (7.6 km)	Intersection of Cañada Road and Highway 92. Bear left (west at the stoplight).
5.4 mi (8.7 km)	Turn right (north) on Skyline Boulevard (Highway 35). The San Andreas Fault crosses the west end of the Highway 92 causeway. A small east-facing scarp reveals the trace of the fault along a low hill on the eastern shore of the reservoir just north of Highway 92.
6.3 mi (10.1 km)	Intersection of Bunker Hill Drive. Continue north on Skyline Boulevard.
6.8 mi (10.9 km)	Cross Crystal Springs Dam and proceed to the parking area to the left on the north side of the dam.
6.9 mi (11.1 km)	**Stop 3—Crystal Springs Dam** (see description below).
7.5 mi (12.1 km)	Return south on Skyline Boulevard to Bunker Hill Drive. Turn left on Bunker Hill Drive.
7.6 mi (12.2 km)	Turn left (north) on I-280.

Continued.

8.0 mi (12.9 km) **0.0 mi (0.0 km)**	**Stop 4—I-280 Rest Area [northbound only] (see description below).** Restrooms are available. **Reset the odometer mileage to zero.** Continue north on I-280.
5.5 mi (8.8 km)	Exit on Skyline Boulevard (Highway 35—Pacifica exit).
6.0-7.0 mi (9.7-11.3 km)	Note the topography along this scenic route between I-280 and San Bruno Boulevard. Skyline Boulevard follows Buri Buri Ridge along the east side of the San Andreas Rift valley northward to Daly City. Look to the west to get a glimpse of San Andreas Reservoir, originally San Andreas Lake, a historic natural sag pond from which the name of the San Andreas Fault was derived. Sweeney Ridge is on the west side of the Reservoir. Skyline Boulevard follows and crosses the San Andreas Fault (or splay of faults) in a number of places along the route.
9.0 mi (14.4 km)	Turn left on Sharp Park Drive.
9.7 mi (15.6 km)	Turn right to the park access lane to Milagra Ridge just past College Drive.
9.9 mi (15.9 km)	**Stop 5—Milagra Ridge** (part of Golden Gate National Recreation Area; see description below). Return east to Skyline Boulevard (Highway 35). Turn north on Skyline.
14.4 mi (23.2 km)	Exit on Highway 1 South.
15.9 mi (25.6 km)	Exit at Palmetto Drive. It is a hard-right turn onto Palmetto Drive.
16.7 mi (26.9 km)	Bear left of Westline Drive.
17.2 mi (27.7 km) **0.0 mi (0.0 km)**	**Stop 6—Mussel Rock Park** (see description below). **Reset the odometer mileage to zero.** Return north on Westline Drive. Bear Right on Palmetto.
1.3 mi (2.1 km)	Continue straight on Palmetto past the McDonald's restaurant.
1.8 mi (2.9 km)	Take Highway 1 South.
4.3 mi (6.9 km)	Mori Ridge (part of Golden Gate National Recreation Area) parking area on the right; however, continue south on Highway 1 past the large field in the abandoned Pacifica limestone quarry on the right.
5.7 mi (9.2 km)	Turn right on San Marlo Way (this small road takes you into the Rockaway Beach Shopping Area). Proceed to a parking area at the north end of Rockaway Beach.
5.9 mi (9.5 km) **0.0 mi (0.0 km)**	**Stop 7—Rockaway Beach and Pacifica Quarry** (see description below). Restaurants and public restrooms are available in the Rockaway Beach Shopping Center. **Reset the odometer mileage to zero** at the main intersection for the shopping center on Highway 1. Continue south on Highway 1.
1.1 mi (1.8 km)	Highway 1 crosses San Pedro Creek. The creek follows the approximate trace of the Pilarcitos Fault.
1.1-3.2 mi (1.8-5.1 km)	**Rolling Stop 8—San Pedro Mountain and the Devil's Slide** (see description below). (Note: "rolling stop" means continue driving to recommended stop locations described below, but observe features in the surrounding landscape as you carefully drive by.)
3.2 mi (5.1 km)	**Rolling Stop 9—Montara Mountain** (see description below).

Continued.

4.1 mi (6.6 km)	McNee Ranch State Park/Gray Whale Cove State Beach parking area is on the east side of Highway 1. An old railroad cut near the parking area is a good place to look at the weathered Montara Granite. An even better place to look at the Montara Granite is at Stop 10.
5.5 mi (8.8 km)	**Stop 10—Montara State Beach** (see description below). Restrooms are available. Continue south on Highway 1.
7.5 mi (12.1 km)	Turn right (west) on California Avenue.
7.9 mi (12.7 km)	**Stop 11—James V. Fitzgerald Marine Preserve** (see description below). Restrooms are available. Return by California Avenue to Highway 1 and continue south.
8.6 mi (13.8 km)	Turn right (west) on Cypress Avenue.
9.1 mi (14.6 km)	Turn left (south) on Airport Avenue.
9.2-11.2 mi (14.8-18.0 km)	**Rolling Stop 12—Seal Cove Fault along Airport Avenue** (see description below). Continue south on Airport Avenue into Princeton on Half Moon Bay.
11.3 mi (18.2 km)	Turn right on Harvard Avenue.
11.4 mi (18.3 km)	Turn right on West Point Avenue.
11.7 mi (18.8 km)	Turn left into the Pillar Point Marsh Preserve (GGNRA) just before the entrance to the Pillar Point Air Force Station.
11.8 mi (19.0 km)	**Stop 13—Pillar Point and Mavericks** (see description below). Restrooms are available. Return north into Princeton. Follow Harvard Avenue east.
12.8 mi (20.6 km)	Turn right on Capistrano Road.
12.9 mi (20.8 km)	Half Moon Bay Brewing Company is on left. Continue south on Capistrano Road.
13.0 mi (20.9 km)	Turn right on Highway 1 South.
17.3 mi (27.8 km)	Turn left (east) on Highway 92.
22.4 mi (36.0 km)	Turn right (south) on I-280.
26.5 mi (42.6 km)	Exit at Edgewood Road to return to the Park and Ride. **End of field trip**.

San Andreas Rift Valley in San Mateo County

The San Andreas Fault runs diagonally in a northwestward direction through San Mateo County in the eastern foothills of the northern Santa Cruz Mountains. From the south, the fault runs through the rural watershed of Corte Madera and upper San Franciscito Creeks, passes through the town of Woodside, and through open space, parklands, watershed reserves around Crystal Springs and San Andreas Reservoirs (fig. 8-2). North of San Andreas Lake, the San Andreas Fault runs through urbanized portions of San Bruno and Daly City before running offshore into the Gulf of the Farallones at Mussel Rock Park. This field-trip guide only focuses on selected public localities and avoids areas within neighborhoods. Unfortunately, many of the urbanized areas underlain by the fault were developed before modern earthquake laws, code, and regulations affecting building construction and neighborhood development were established. The epicenter of the magnitude 7.9 Great San Francisco Earthquake of 1906 is located only several miles offshore of the coast to the northwest of San Mateo County, and the fault ruptured throughout its extent in the county locally causing severe damage in what was mostly a rural region at the time of the earthquake.

Optional Stop A—Interstate 280 Vista Point of Crystal Springs Reservoir

Stop highlights: San Andreas Rift Valley, shutter ridge, serpentinite, greenstone

For groups in a hurry to take advantage of morning low tide along the coast, consider taking a brief orientation stop at the I-280 Vista Point located 0.5 miles (0.8 km) north of the Edgewood Road exit. The Edgewood Road exit is located 2 miles (3.2 km) south of the Highway 92 (Half Moon Bay exit). Note that the Vista Point is accessible only on the north-bound lane of I-280. Southbound travelers should take the Edgewood Road exit on I-280, cross to the other side of the Interstate, then return northward to the Vista Point exit. Parking for about a dozen vehicles is typically available.

The I-280 Vista Point provides an excellent location for an introductory overview about the regional geology of the San Andreas Fault and the northern Santa Cruz Mountains.

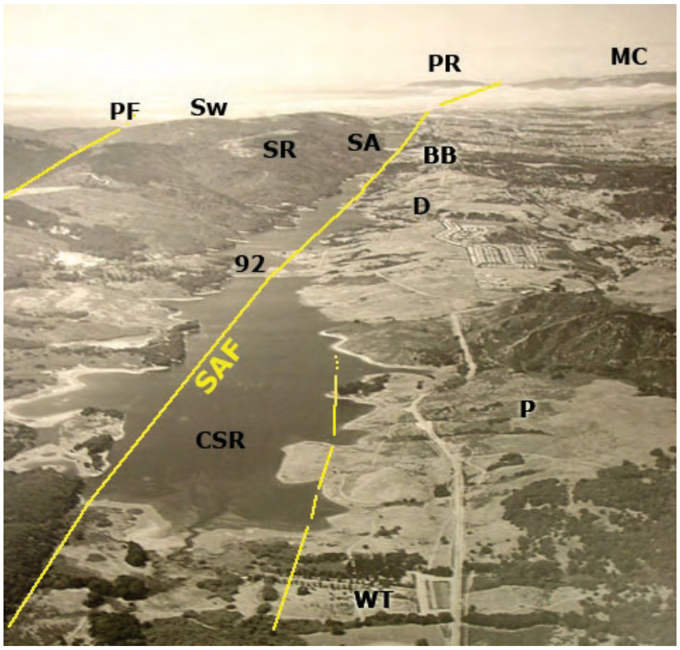


Figure 8-2. This oblique aerial view looks north along the rift valley of the San Andreas Fault (SAF) in the vicinity of Crystal Springs Reservoir (CSR). The photograph was taken from about a mile above the Filoli Estate. The Pulgas Water Temple (WT) is in the foreground. The Highway 92 causeway (92) bisects the reservoir (lower and upper reservoirs, with upper in the foreground). Sawyer Ridge (SR) and Sweeney Ridge (Sw) run between the San Andreas Rift Valley and a valley along the Pilarcitos Fault (PF) in the northern Santa Cruz Mountains. Crystal Springs Dam (D) was built across a narrow gorge cut by San Mateo Creek through the eastern shutter ridge along the San Andreas Fault. This gap divides Pulgas Ridge (P) and Buri Buri Ridge (BB) near San Andreas Reservoir (SA). Fog covers the Golden Gate. Higher peaks of Point Reyes (PR) and Marin County (MC) are in the distance beyond the Gulf of the Farralones. This photograph was taken before the construction of I-280. A similar view appears in Wallace (1990).

The Vista Point provides a sweeping view of the San Andreas Rift Valley along the central portion of the Peninsula segment of the fault. Crystal Springs Reservoir floods the lower portion of the linear rift valley (see figs. 8-1, 8-2, and 8-3). Although published estimates vary, and are often disputed, roughly 186 miles (300 km) of offset has occurred along the mid-section of the San Andreas Fault (south of the Bay Area). In the Bay Area, this amount of offset is divided by the regional fault system. About 108 miles (174 km) of offset in the Bay Area has occurred along the East Bay fault system, whereas 62 miles (127 km) of offset has occurred along the San Andreas Fault/Pilarcitos Fault system in the Santa Cruz Mountains on the San Francisco Peninsula. Only about 13.5 miles (22 km) has been absorbed on the modern Peninsula segment of the San Andreas Fault after about 65 miles (105 km) of offset occurred on the Pilarcitos Fault (McLaughlin and others, 1996; Jachens and others, 1998). Pilarcitos Fault (or Pilarcitos/Montara Fault) is located in the valley on the west side of Sawyer Ridge—shown in figs. 8-1, 8-2 and 8-3. Additional regional right-lateral fault displacements that may total in the range of hundreds of miles occurred along the San Gregorio Fault and other fault systems along the west side of the Santa Cruz Mountain and offshore.

Boulders of serpentinite and greenstone can be viewed along the paths and in the walls around the Vista Point. Serpentinite (or more technically, serpentinized-ultramafic rock) is derived from the mantle or lower oceanic crust and probably originally formed beneath a mid-ocean-ridge spreading center. Massive serpentinite bodies in the Bay Area are part of the Coast Range Ophiolite of Jurassic age. The greenstone is from the Franciscan Complex of Cretaceous age and is abundant throughout the northern Santa Cruz Mountains. The Franciscan Complex represents rocks from the upper ocean crust and consists of rocks formed from submarine volcanism and from deep marine sediments. Greenstone forms from the low-temperature metamorphic alteration of basalt. The original basalt probably accumulated as intrusions or flows on ancient submarine volcanoes on the seafloor. Other sediments that accumulated on the sea bed became layered chert, shale, graywacke sandstone, and limestone. Some of these deposits eventually were metamorphosed into metachert, slate, schist, metasandstone (including metagraywacke), and marble. Over a 100-million-year period, these rocks migrated great distances

Figure 8-3. View of Crystal Springs Reservoir in the rift valley of the San Andreas Fault. This view is from the northwest end of the I-280 Vista Point looking northwest toward Sawyer Ridge beyond the reservoir. Interstate 280 is not shown in the foreground. The Pilarcitos Fault is in the valley on the west side of Sawyer Ridge.

from their place of origin, carried by the tectonic plates on which they were deposited. These rocks were wedged against the North American Plate along the subduction zone that existed here at the time and were accreted onto the western North American continental margin. Slivers of serpentinite are found within the Franciscan Complex. Wahrhaftig and Murchey (1987) and Elder (2001) provide discussions about the geology of the Franciscan Complex in Marin County in the headlands west of the Golden Gate.

Stop 1—Filoli Center (optional stop on Cañada Road)

Stop highlights: San Andreas Rift Valley, offset alluvial fan deposits, sidehill bench, historic estate and gardens

The Filoli Center is a 654-acre estate with a Georgian-style mansion surrounded by 16 acres of formal gardens. The Filoli Estate was built for the family of William Bowers Bourn II. The building was designed by Mr. Bourn's friend and San Francisco architect, Willis Polk, who also designed the nearby Pulgas Water Temple. Mr. Bourn amassed a fortune from the Empire Gold Mine, a bedrock gold mine in the Mother Lode in Grass Valley, California. He was also owner and president of the Spring Valley Water Company that comprised Crystal Springs Lake and surrounding lands (now managed by of the San Francisco Water Company). The Bourns were supposedly severely traumatized by the San Francisco's great earthquake disaster of 1906. The failures of the water system in San Francisco contributed to the massive fire damage after the earthquake. The Bourns had their country mansion built 10 years after the 1906 disaster, probably without the knowledge of the proximity of the great earthquake fault nearby. After Mr. Bourn's death in 1936, the estate was purchased by the William P. Roth family (owners of the Matson Navigation Company). Mrs. Lurline B. Roth donated 125 acres of the estate (including the mansion and gardens) to the National Trust for Historic Preservation in 1975, and it is now operated by the Filoli Center.

Many geologic and paleoseismic investigations have been conducted in the Filoli area because landscape features and sedimentary deposits along the San Andreas Fault are well preserved and relatively undisturbed by past human activity. The Filoli Estate provided an ideal area to study the fault because in some identified areas sediments have been accumulating for thousands of years in wetlands and along stream floodplains that are cut by the fault. Seismologists dig trenches in undisturbed ground across fault zones in search of clues in the sediments that might reveal information about the frequency and intensity of past earthquakes. Dates of past seismic events can be estimated by using radiocarbon dating methods to determine the age of organic material extracted from sediment that were either cut by faulting or overlie breaks or features associated with past fault movements.

The main trace of the fault passes through the undeveloped Filoli Center grounds several hundred feet to west of the mansion and gardens. The fault created an escarpment and sidehill bench in the area southeast of the mansion where the fault runs through a prehistoric Ohlone (Native American) habitation site. Nearby, Spring Creek crosses the fault where an embankment reveals alluvial-fan sediments that are offset by the fault, including slip from the 1906 earthquake. In 1993 to 1994, trenches were dug in a meadow and sag pond area near the creek about a half mile south of the mansion. The trenches were dug to evaluate the fault and its paleoseismicity (Wright and others, 1996; Hall and others, 1999). Hall and others (1995) interpreted a total slip from the 1906 earthquake in the range of 8 feet (2.5 m) in the fault zone in the Filoli area. The magnitude 7.0 earthquake of 1838 that occurred on the San Francisco Peninsula also produced about 5 feet (1.5 m) of offset along the San Andreas Fault. Nearby in vicinity of a ranger's residence, a row of mature cypress trees is offset where it crosses the fault.

Please note that the significant geologic features associated with the San Andreas Fault are not accessible by the general public at the estate and gardens area of the Filoli Center. However, the hillslope associated with the east-facing escarpment along the west side of the San Andreas Rift Valley is visible from the estate grounds (fig. 8-4). Guided trips to look at natural features on the non-public grounds require an escort by Filoli volunteer staff, and reservations are required well in advance. See the Filoli website for hours, access fees, and other information (http://www.filoli.org/).

Figure 8-4. The Filoli Center (estate and formal gardens) is located on Cañada Road west of I-280 near the Edgewood Road exit. The San Andreas Fault runs through the forest west of the developed estate grounds where it offsets alluvial fan deposits. Skyline Ridge is in the distance.

Stop 2—Pulgas Water Temple (optional stop on Cañada Road)

Stop highlights: San Andreas Rift Valley, Franciscan Complex sandstone, greenstone, serpentinite

The Pulgas Water Temple is located along Cañada Road between the Filoli Estate and the southern end of Crystal Springs Reservoir (fig. 8-5). The Pulgas Water Temple was designed by San Francisco architect Willis Polk and has a Roman temple style. The temple was constructed in 1934. It marks the western terminus of the water pipeline and tunnel system that drains from the Hetch Hetchy Reservoir in the Sierra Nevada and supplies the City of San Francisco and other municipalities with water stored in Crystal Springs Reservoirs and San Andreas Lake. The Pulgas Water Temple was renovated in 2004; the parking area serves as a trailhead for the Fifield-Cahill Ridge Trail. Note that the parking area is closed on the weekends except for special events.

The drive northward along Cañada Road provides a less-stressful way of viewing the San Andreas Rift Valley and Crystal Springs Reservoir than driving along Highway 280. Outcrops of Franciscan sandstone, greenstone, and some serpentinite can be seen in the field and road cuts along Cañada Road between Filoli and Highway 92 and along the shore of Crystal Springs Reservoir.

Stop 3—Crystal Springs Reservoir Dam

Stop Highlights: A high dam constructed near the San Andreas Fault, shutter ridge, Crystal Springs Canyon

Figure 8-5. The Pulgas Water Temple is located along Cañada Road just north of the Filoli Center. The trace of the San Andreas Fault that ruptured in the 1906 earthquake runs along the base of the mountainside in the distance.

Crystal Springs Dam is accessible along Skyline Boulevard between the Half Moon Bay exit for Highway 92 (west) and Haynes Road exit on I-280. Skyline Boulevard runs parallel to I-280 on the east side of Crystal Springs Reservoir. Parking for the dam and the shoreline Sawyer Camp Trail is located along Skyline Boulevard just north of the dam. Outcrops of serpentinite can be seen along the road near the dam. Serpentinite soils in the vicinity host a manzanita scrub forest along the shore of the reservoir. Note that the reservoir shoreline and surrounding watershed area is closed to public access.

Construction of Crystal Springs Reservoir began in the 1870s with removal of all vegetation and manmade structures from a 9 mile (14.5 km) stretch along upper San Mateo Creek Valley. The reservoir was part of the extensive water system designed by the Spring Valley Water Company of San Francisco to help quench the demands of the rapidly growing city. Construction of the dam across Crystal Springs Canyon was completed in 1889, and heavy rains of the following year filled the reservoir to capacity in a little over a year (nearly a decade sooner than was anticipated). At the time of its construction the dam was the largest in the world, designed to hold back 32 billion gallons (120 billion liters) of water. The dam is made of concrete and was originally about 120 feet (37 m) high. The dam was raised to 145 feet (44 m) in 1890 and to 149 feet (46 m) in 1911. It is 120 feet (37 m) thick at its base and about 20 feet (6 m) thick at the top. Crystal Springs Reservoir is bisected into lower and upper reservoirs by the causeway traversed by Highway 92. The Crystal Springs Dam is on the Lower Reservoir.

Crystal Springs Dam is located ominously close to the San Andreas Fault; the fault trace runs parallel to the dam several hundred feet to the west and submerged beneath the reservoir. Crystal Springs Canyon is a narrow gorge cut through the eastern shutter ridge of the San Andreas Fault. Buri Buri Ridge is north of the canyon, and Pulgas Ridge is south of the canyon. The dam survived both the 1906 and 1989 earthquakes with no apparent damage. The drainage tunnel of the San Andreas Lake (reservoir) dam to the north and upstream of Crystal Springs Reservoir was offset and severely damaged by motion along the San Andreas Fault during the 1906 earthquake, but the earth-fill dam itself survived undamaged. It is interesting to note that the significance of the San Andreas Fault was unknown at the time of the construction of Crystal Springs Dam.

Stop 4—I-280 Northbound Rest Area

Stop Highlights: San Andreas Rift Valley overlook, Crystal Springs Reservoir, serpentinite

The northbound I-280 is another optional field-trip stop that provides a sweeping vista of the San Andreas Rift Valley, Sawyer Ridge, and Crystal Springs Reservoir (fig. 8-7). A

Figure 8-6. This view of Crystal Springs Reservoir Dam is from along Crystal Springs Road beneath the I-280 bridges over Crystal Springs Canyon. Skyline Boulevard crosses the dam. Sawyer Ridge is in the distance.

walkway leads to an overlook area around a statue of Father Junipero Serra, the founder of the California missions. The walls along the path and of the restroom facility are made of serpentinite and greenstone from local sources (see discussion for Stop A above).

Figure 8-7. Franciscan Padre Junipero Serra (1713-1784) is credited for founding the mission which led to the Spanish colonization of California. He was appointed to establish the Missions in Alta (upper) California in 1767 and spent the rest of his life pursuing that effort. He aided an expedition in locating San Francisco Bay, and before he died, he founded nine of the California missions. Although Serra's statue at the rest area on northbound I-280 should probably be pointing at the bay, instead it looks like it points across the interstate toward the San Andreas Fault.

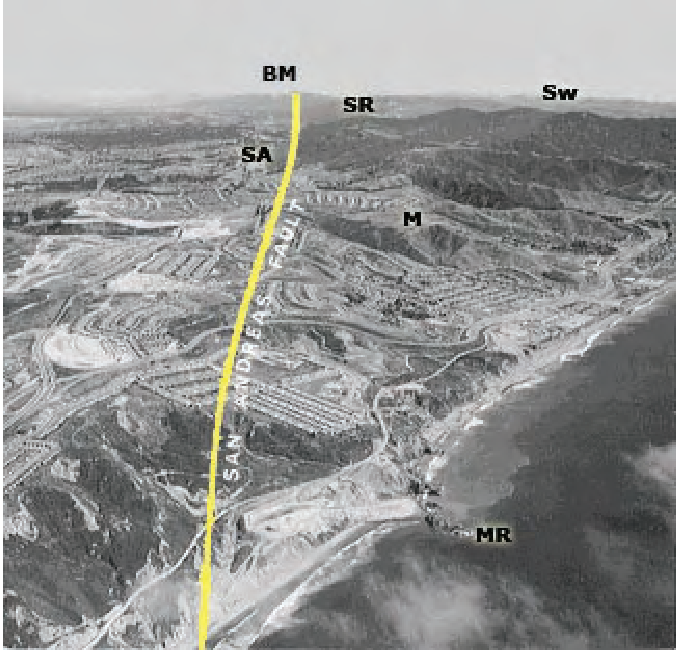


Figure 8-8. Aerial view of the San Andreas Fault in the northern Santa Cruz Mountains in San Mateo County. This view is looking south toward the coast at Mussel Rock Park and neighborhoods of Daly City. Labeled features include Mussel Rock (MR), Milagra Ridge (M), San Andreas Lake (SA), Sawyer Ridge (SR) and Sweeney Ridge (Sw). Black Mountain (BM) in northern Santa Clara County is in the distance. This photograph was probably taken in the early 1960s, when most of the residential construction was nearly completed in the Daly City region. Note the trace of Highway 1 along the sea cliffs in the Mussel Rock area. A massive landslide is near the "SAN" of the San Andreas Fault label on the image. Today, very little remains of the trace of the highway due to coastal erosion and landsliding (see fig. 8-10). The landscape east of Mussel Rock is underlain by the Merced Formation. The Merced Formation is a mile thick sequence of poorly consolidated sedimentary materials that accumulated in coastal and nearshore marine environments during the late Pliocene and Pleistocene epochs.

Northern San Mateo County

Stop 5—Milagra Ridge (Golden Gate National Recreation Area)

Trip highlights: San Andreas Rift Valley, coastal view of Pacifica region, butterfly preserve

Milagra Ridge offers a good view of the urbanized area along the San Andreas Fault and along the coast (see fig. 8-8). The preserve is a "habitat island"—a remnant of coastal prairie now surrounded by urban development. In the past, the area was used by native Ohlone people. The land was then later claimed by Spanish settlers and Mexican rancheros. A gun battery was installed on the ridge during World War II, and a Nike missile station was installed during the Cold War. Extensive urban development of the surrounding area began in the late 1950s. In 1984, the land was added to the Golden Gate National Recreation Area. The parkland is a preserve for threatened and endangered species—the Mission blue and San Bruno elfin butterflies and the California red-legged frog.

Parking is extremely limited on a small access road reached by Sharp Park Road opposite the College Drive access to Skyline College. A short uphill trail that starts at the parking area leads to an overlook of the Pacifica area and headlands along the coast. On the east side of the ridge, the rift valley of the San Andreas Fault is clearly visible as it runs through the urban setting adjacent to Skyline Boulevard. Sweeney Ridge to the south is also part of the Golden Gate National Recreation Area. It was on Sweeney Ridge in 1769 that Spanish explorer Captain Gaspar de Portola recorded in his diary an account of the first sighting of what would become the busy seaport harbor and metropolitan region around San Francisco Bay. For more information, see the National Park Service websites for Milagra Ridge (http://www.nps.gov/goga/clho/miri/) and Sweeney Ridge (http://www.nps.gov/goga/clho/swri/).

Stop 6—Mussel Rock Park

Trip highlights: Quaternary Merced Formation, Franciscan greenstone, landslides, coastal erosion, urban geohazards

Mussel Rock Park is situated along the northern San Mateo Coast at Daly City. The Peninsula segment of the San Andreas Fault runs out to sea just north of Mussel Rock (figs. 8-8, 8-10, and 8-11). The fault trace is obscured by landslide deposits and an old garbage dump, now filled, in the park area. However, the presence of the fault can be seen in the bedrock contrast from Cretaceous-age greenstone of the Franciscan Complex of Mussel Rock itself located west of the fault and the late Pliocene to Quaternary-age sediments of the Merced Formation west of the fault. Current theory is that the epicenter of the 1906 earthquake probably occurred along the offshore segment of the San Andreas Fault several miles north of Mussel Rock in the region offshore from Fort Funston at 37°70’N, 122°50’W (location data from the website *Anniversaries of Notable California Earthquakes* at http://www.consrv.ca.gov/cgs/rghm/quakes/eq_calender.htm). The northern end of the Peninsula segment of the San Andreas Fault experienced about 13 feet (4 m) of right-lateral displacement and experienced near the full intensity of the 7.9 magnitude 1906 San Francisco earthquake. However, the area along the fault was essentially undeveloped at the time of the great earthquake.

The San Andreas Fault runs through urbanized areas of San Bruno and Daly City. Although developers were probably aware of the fault’s location, construction of many residential homes and businesses proceeded because earthquake fault zone assessment and zoning laws were not yet established. The Alquist-Priola Earthquake Zoning Act of 1973 set forth the minimum fault investigation and approval requirements for all California cities and counties. The Act requires fault investigations for developments of four or more houses and subdivisions of five or more parcels. No structure subject to the provisions can be placed closer than 50 feet to a fault unless studies approved by a local authority support a lesser setback, but no structure can cross the trace of a fault with established earthquake potential. An additional hazard to property and structures in this area is from landsliding. A number of homes have been destroyed or severely damaged

Figure 8-9. View of the San Andreas Rift Valley on the west side of Milagra Ridge. Milagra Ridge is protected habitat within Golden Gate National Recreation Area. In the distance, a housing development runs along the hillsides east of the rift valley.

Figure 8-10. Mussel Rock is part of a large outcrop belt of greenstone that forms a small promontory and sea stacks on the San Mateo County coast in Daly City. This belt of greenstone of the Cretaceous Franciscan Complex is on the west side of the San Andreas Fault.

Figure 8-11. A massive landslide complex at Mussel Rock Park masks the main trace of the San Andreas Fault. Note the high, barren slump escarpment in the background. Ongoing coastal erosion at the toe of this slide area promotes the landward migration of the high wall of the landslide escarpment. Numerous homes have been destroyed, damaged, or condemned along this coastal slide area of Daly City.

Figure 8-12. View looking northward from Mussel Rock Park along the sea cliffs at Thornton Beach State Park. The rolling hill slope in the foreground is part of the toe area of the large landslide complex at Mussel Rock Park. The sea cliffs are exposures of the Merced Formation. The Ocean Shore Railroad built along this section of coast in 1905 to 1906 was severely damaged by the 1906 earthquake. Because of ongoing troubles due to landsliding, the rail line was abandoned in 1920. In the 1930s, the rail line was widened to accommodate Highway 1. However, shortly after the magnitude 5.3 earthquake on March 22, 1957, the route was once again abandoned. Today only a trace of the highway cut can be seen about midway up the sea cliff. See figure 8-8 for comparison.

because they were built too close to the sea cliff on unstable ground.

Use caution when exploring the landslide area, the greenstone outcrops near Mussel Rock, or the beach below the sea cliffs. Do not attempt to go on the beach during high tide or during high surf. There is not enough space along the upper beach to escape from rogue waves, and material is constantly sloughing off the cliff. The same is true of the cliffs along the upper landslide escarpment. Open fractures occur throughout the landslide area and may not be visible beneath vegetation cover.

Only the lower part of the Merced Formation crops out in the Mussel Rock Park area. These sandstone beds are steeply dipping near the fault zone, but dip more gently northward along the coast at Thornton State Beach (north of Mussel Rock Park)(fig. 8-12). The Merced Formation consists of interbedded sandstone and shale and contains some fossiliferous marl (calcareous mudstone) and conglomeratic beds. These deposits accumulated in marine shelf, intertidal, and coastal sedimentary environments as sea level rose and fell during the ice ages of the Quaternary Period. As the modern strand of the Peninsula segment of the San Andreas Fault developed, the land steadily rose in late Quaternary time, eventually elevating the once marine sediments to their present elevation of 750 feet (229 m) in the bluffs along the San Andreas Fault Zone at Mussel Rock Park. A better place to visit the Merced Formation is at Fort Funston located several miles north of Mussel Rock Park. The geology of the Merced Formation is described by Clifton and Hunter (1987) and Andersen and others (2001). For more information about Fort Funston, see the National Park Service website at http://www.nps.gov/goga/fofu/.

Stop 7—Pacifica Quarry and Rockaway Beach

Stop highlights: Permanente Terrane, Calera Limestone, Pilarcitos Fault, coastal headlands

Rockaway Beach is a good place to view the headlands along the northern San Mateo Coast and to access the Pacifica Quarry. The Rockaway Beach Shopping Center usually has ample parking. However, field-trip participants should be given a time to meet at the northwest end of the rip-rap beach wall because the beach and shops grow more crowded during mid-day, and it will probably not be possible to park vehicles together near the beach.

From the rip-rap seawall area it is possible to see a geomorphic expression of the Pilarcitos Fault along the north facing flank of the San Pedro Point headlands to the south of Rockaway Beach (see fig. 8-13). Unfortunately, there are no bedrock exposures along the Pilarcitos Fault that are accessible to the public. The presence of the fault is revealed by a change in bedrock lithology. On the east side of the fault, the bedrock consists of Franciscan Complex (mostly greenstone and sandstone exposed in the Rockaway Point headlands).

The bedrock on the west side of the fault consists of interbedded sandstone and shale (turbidites) of Paleocene age. These turbidites are exposed in road cuts along Highway 1 south of Pacific Beach and in the San Pedro Point headlands (see figs. 8-16 and 8-17 described in Stop 8).

Pacifica Quarry is an inactive limestone and greenstone mine on the south end of the Mori Point headlands at the north end of Rockaway Beach (figs. 8-14 and 8-15). Small-scale limestone mining began in the Pacifica area in the early 19th century, when lime was used primarily for whitewash for buildings at the Presidio in San Francisco. The larger quarry began operation in 1904, a year before the Ocean Shore Railroad was established. Much of the limestone mined at the site was probably used for cement in San Francisco's reconstruction after the 1906 earthquake. Shortly after the city of Pacifica was incorporated in 1957, the community voted to donate much of the undeveloped coastal land, including Mori Point, to the National Park Service (Golden Gate National Recreation Area) in an effort to prevent further development. The restored Calera Creek is considered habitat for the endangered California red-legged frog. The Rockaway Beach Quarry Trail crosses through the quarry area.

The Calera Limestone Member of the Franciscan Complex is about 230 feet (70 m) thick. The Calera Limestone is part of the Permanente Terrane, a split-up block of Franciscan rocks that also crops out in the foothills along the San Andreas Fault in Santa Clara County, including at El Toro Peak in Morgan Hill, Calero County Park, and in the Permanente Quarry in the Permanente Creek area of the larger Stevens Creek watershed near Cupertino, California. The Calera Limestone Member consists mostly of a dark gray, fine grained (micritic) limestone locally recrystallized to crystalline calcite masses and contains interbedded nodular layers of chert. The Calera Limestone is also locally cut by greenstone dikes (originally of basalt composition).

Figure 8-14. Calera Limestone forms the Mori Point headlands at the north end of Rockaway Beach. Calera means limestone quarry or limekiln in Spanish. Mori Point is now part of the Golden Gate National Recreation Area.

Figure 8-13. View looking south along Rockaway Beach towards Rockaway Point and the more distant San Pedro Point headlands and Pedro Rock (a sea stack in the distant right). Cretaceous-age sandstone and greenstone of the Franciscan Complex crop out on the headlands of Rockaway Point. Pacifica State Beach is in the bay to the south of Rockaway Point. San Pedro Creek, at the south end of Pacifica Beach, follows the trace of the Pilarcitos Fault and runs out to sea along the north side of the San Pedro Point headlands (far distance, right).

Figure 8-15. The Calera Limestone was mined in the Pacifica Quarry. The rock is dark, layered limestone and marble, with interbedded layers of chert. Locally, the rock contains some small greenstone dikes and veins of calcite. Large blocks of this material can also be examined in the rip-rap seawall at the parking area at Rockaway Beach.

The Calera Limestone formed by the accumulation original lime ooze sediments (including planktonic foraminifera and coccoliths) deposited on the ocean floor. Over time these sediments became compacted and lithified, and later underwent a moderate degree of metamorphism during deep burial and accretion onto the North American continental margin. Fossils found in the Calera Limestone indicate a middle Cretaceous age (Albian to mid-Cenomanian stages, about 105 to 94 million years ago). The presence of tropical microfauna suggests that the calcium-carbonate deposits of the Calera Limestone have been transported a significant distance from their place of origin by plate-tectonic movement (Tarduno, 1985). In the modern ocean, the carbonate-compensation depth (CCD) is typically about 2.5 miles (4 km) deep in tropical latitudes. Below the CCD, carbonate material (such as plankton skeletal material) tends to dissolve in cold water conditions before it can be incorporated into sediments. However, in low-latitude regions, carbonate sediment generation is more rapid, and carbonate ooze accumulates on the deep-ocean seabed, particularly on elevated platforms or seamounts and is purest where it is far from terrigenous sediment sources. Calcium carbonate is also generated by ocean-derived fluids reacting with ultramafic rocks in the formation of serpentinite, and large modern deposits of deep-sea carbonates associated with seafloor springs have been discovered in association with warm-water vents on the sea bottom (Fruh-Green and others, 2003; Schroeder, 2002). However, these deep-sea vent deposits are typically associated with rough ocean-bottom terranes and have a different microfossil and invertebrate fauna than those observed in the more evenly bedded Calera Limestone and have a high concentration of magnesium carbonate.

Stop 8—San Pedro Mountain and the Devil's Slide (rolling stop)

Stop highlights: Paleocene turbidites, coastal headlands, landslide hazards

In the Devil's Slide area, most of the roadside pulloffs along Highway 1 are posted "no stopping" for good reason. The spaces are too narrow and small and the traffic is too heavy and fast to be considered safe for a field-trip stop. However, notable geologic features can be seen along the highway as you drive.

South of Pacifica State Beach, Highway 1 crosses the Pilarcitos Fault (near San Pedro Creek) and climbs to the crest of San Pedro Ridge through a eucalyptus forest. Near the crest of the ridge, steeply dipping and folded layers of shale, sandstone, and calcareous marl of Paleocene age crop out in road cuts along the highway (fig. 8-16). These same units are exposed in Pedro Rock at the northwest end of San Pedro Point (fig. 8-17). Paleocene-age conglomerate and granitic breccia in the road cut rests unconformably on Mesozoic-age granitic rocks and gneiss of Montara Mountain (Salinian basement complex) to the south. The sedimentary units formed as deep-sea fan deposits (inner- and mid-fan channels, channel margin, and interchannel settings) that accumulated as turbidity flows into a restricted, deep, tectonically active basin setting (Nilsen and Yount, 1987). Mineral clasts in arkosic, lithic, and unusual calcareous marl and sandstones within the turbidite sequence suggest that sediments were derived from Salinian basement, with the calcareous material derived from marble roof pendant structures in the granitic terrane, similar to carbonate rocks exposed in the Ben Lomond Mountain and Fremont Peak areas to the south.

The Devil's Slide area begins just west of the pass on the west side of San Pedro Ridge and extends for about 0.8 mile (1.3 km) along Highway 1 on the northwest flank of Montara Mountain (fig. 8-18). The landslide is occurring where steeply dipping, faulted and folded Paleocene rocks are slipping above a steeply inclined surface of underlying weathered Mesozoic granitic bedrock of Montara Mountain. Several landslide chutes and failure zones are present in the area, and the glide planes of the slump blocks extend as much as 150 feet (46 m) below the surface. The landslide extends from 900 feet (275 m) high on the mountain down to sea level (Williams, 2001).

Figure 8-16. Road cuts along Highway 1 expose interbedded layers of Paleocene-age deep-sea-fan deposits (turbidites). This view is looking east from a small pull off at the top of the ridge of San Pedro Mountain. Note that this pull off is not recommended as a field-trip stop because of high traffic volume along the highway. Coastal travelers can more safely access similar deposits of Cretaceous age at Bean Hollow State Beach or near Pigeon Point south of Half Moon Bay.

The landslide complex at Devil's Slide has a long and expensive history. Landslide failures disrupted travel along the first road built across the slide area in the late 1890s, and the road was eventually abandoned. Starting in 1905, the Ocean Shore Railroad attempted to operate a rail line across the area below the present road level, but it was abandoned in the 1920s because of the chronic troubles with landsliding at Devil's Slide and elsewhere along this coastal route. The State Department of Highways completed the first version of the coastal highway along the abandoned rail line in 1936, and this route in part is

Figure 8-17. Pedro Rock at the south end of Point San Pedro consists of steeply dipping beds of Paleocene-age sandstone and shale (covered locally with bird guano). Darrow (1963) described unconformable relations between the Paleocene sedimentary rocks and sedimentary rocks of late Upper Cretaceous beds on San Pedro Point (to the right). Whether these Upper Cretaceous sediments are in conformable contact with the Salinian granite is unclear. A remnant of the old Ocean Shore Railroad bed is visible along the shore (lower right).

Figure 8-18. Devil's Slide. This view is looking south from one of the small roadside pull offs along Highway 1. Portions of the San Mateo Coast south of Shelter Cove (including San Pedro Rock) have been incorporated in the Golden Gate National Recreation Area. A ruin of a World War II-era gun emplacement is visible on top of a headland at the south end of Devil's Slide.

Highway 1 today. However, landsliding and road closures have constantly plagued the route, and millions of dollars have been expended in endless repairs. CalTrans (California Department of Transportation) is currently evaluating plans to construct a 4,000-foot (1,220 m) tunnel through Montara Mountain to bypass the slide area. For more information, see the discussion by Williams (2001) about the engineering geology of the Devil's Slide.

Stop 9—Montara Mountain (rolling stop)

Stop highlights: Salinian granite, coastal headlands

Cretaceous-age granitic rocks of the Salinian Block are exposed in coastal headlands and cuts along Highway 1 on Montara Mountain. Granitic rock is exposed along the shore at Gray Whale Cove State Beach and along trails and in a historic Ocean Shore Railroad cut in McNee Ranch State Park. Note that the granitic rock is deeply weathered except in eroding exposures along the beaches. This gives the Montara Mountain granitic bedrock a rusty-orange appearance, whereas the fresh exposures along the beach are pale gray (fig. 8-19). Quartz-rich dikes and dark mafic dikes cross cut the granitic rock in many locations. The rock was originally named the Montara Granite, and later renamed the Montara Quartz Diorite (Lawson, 1895a, Lawson, 1895b, and Lawson, 1914).

The Salinian Block is a 15,500 square mile (40,000 km^2) fault-bounded block of granitic and metamorphic basement along California's coastline, west of the San Andreas Fault (fig. 8-20). The block is structurally isolated from other Cordilleran granitic terranes of the West Coast by large-scale, right-lateral movements including about 200 miles (320 km)

Figure 8-19. Headlands along the coast side of Montara Mountain. Cretaceous-age Salinian granitic rocks make up the core of Montara Mountain. This view is looking north from a small pull off on Highway 1 north of Gray Whale Cove State Beach.

of movement on the San Andreas Fault system. The Salinian Block is surrounded by oceanic crust basement (Franciscan Complex and Coast Range Ophiolite) along most of its length. The Salinian Block is in itself split into several smaller, structurally complex blocks. The granitic exposures on Montara Mountain are part of a northern block that includes disjointed exposures such as the Farallon Islands, Point Reyes, and Bodega Head. The granitic exposures on Ben Lomond Mountain, the Monterey Peninsula, Santa Lucia Range, and the Gabilan Range are within a central block. Chemical and petrographic characters of the Salinian Block granitic rocks and their metamorphic frameworks suggest that the crystalline basement rocks originated somewhere within the Cordilleran volcanic arc in southern California or possibly from a similar setting much farther to the south. These rocks moved northward to their present location along fault systems that predate the San Andreas Fault and then along the San Andreas Fault from its time of inception starting about 23 million years ago. Radiometric ages of the granitic rocks in the Salinian Block range from about 70 to 120 million years (within the Cretaceous Period), but radiometric ages of granitic samples from Montara Mountain are in the range of about 82 to 95 million years (Ross, 1983; Mattinson, 1990, Kistler and Champion, 1997).

Figure 8-20. Map showing granitic bedrock provinces of California highlighting the extent of the Salinian Block. Exposures of granitic bedrock in the Salinian Block are shown in red. The Salinian Block extends offshore to the shelf margin to some undetermined extent north and west of the San Francisco Bay Area. The block is bounded on the east by the San Andreas Fault and on the west in the southern part by the Sur-Nacimiento and San Gregorio Fault systems. The western side of the northern Salinian Block is probably bounded by faults in the offshore region along the continental shelf margin.

Please note that it is advised not to stop along the Highway 1 on Montara Mountain or attempt to cross the busy highway into parking areas. Instead, consider using the Stop 10 (Montara State Beach) locality described below.

Stop 10—Montara State Beach

Stop highlights: Salinian granite, offset Quaternary marine terraces, shore dune and lignite deposits

Montara State Beach is in a cove between the Montara Mountain headlands to the north and headlands by the town of Montara to the south. A northwest trending fault zone runs offshore at the northern end of Montara Beach along the southwest side of Montara Mountain. Another northwest trending fault, the Montara Fault, extends offshore in the rocky headlands at the south end of the beach. A small fault with some apparent thrust offset is exposed in the sea cliff and displaces Salinian granite over marine terrace deposits of Quaternary age (fig. 8-21).

Three marine terraces are recognized along the coast between Montara Beach and Half Moon Bay (to the south) and were described by Jack (1969). These marine terraces are, from oldest to youngest, the San Vicente, the Montara, and the Half Moon Bay. The ages of the terraces are still being debated, and their correlation to terraces elsewhere along the coast is made difficult by the complexity of fault motion relative to marine terrace development in the area, as well as by a lack of datable materials.

Figure 8-21. This image shows a small fault where Montara granitic rock has been thrust over younger Quaternary marine terrace deposits. The basal conglomerate of the San Vincente terrace deposits rests unconformably on an irregular wave-cut bench surface of weathered granite. Thrust faulting (with possibly more significant strike-slip offset) occurred after the San Vicente terrace deposits had accumulated.

San Vicente Terrace Deposits

The San Vicente marine terrace deposits are exposed in a faulted block near sea level at the south end of Montara State Beach (see fig. 8-21). These deposits rest unconformably on an irregular wave-cut bench surface on underlying Salinian granitic rocks. The terrace deposits consist of a basal pebble conglomerate of marine origin that contains clasts (pebbles to cobbles) of mafic volcanic rock and other materials derived from the Franciscan Complex (these are not present in the younger terrace deposits). It also contains material derived from the local granite with some pieces ranging to boulder size. Some cobbles in the San Vicente preserve marine pelecypod (*Pholad*) borings.

Terrace deposits with pebbles of Franciscan derivation also occur 200 to 560 feet (61 to 170 m) above sea level in the region south of Montara Beach. This variation in elevation suggests that the San Vicente terrace has experienced significant post-depositional tectonic tilting and faulting. In addition, erosion has highly degraded any surface expression reminiscent of younger marine terraces, such as those preserved along the coast near the Davenport area in Santa Cruz County (Weber and Allwardt, 2001). Cross-cutting relationships in the sea cliff exposures suggest that some of the tectonic tilting and faulting took place before deposition of the next younger Montara marine terrace. The age of the San Vicente marine terrace is not well determined, but is likely older than 300,000 to 500,000 years.

Montara Terrace Deposits

Deposits of the Montara marine terrace are well exposed in the sea cliff below the parking area at Montara State Beach (fig. 8-22). The terrace deposits consist of (from youngest to oldest): (1) a well sorted wind-blown sand facies [eolianite], (2) a lignite bed, (3) an upper arkosic, alluvial gravel facies (containing Montara Mountain granodiorite), and (4) a lower beach and shallow-marine member containing material of local granitic rock derivation. At Montara State Beach the Montara terrace deposits rest unconformably on San Vicente terrace deposits. At Montara Point (about a mile south of the beach), slip along the Point Montara Fault displaces the Montara marine terrace at 18 feet (5.5 m) elevation north of the fault and 95 feet (29 m) south of the fault (Jack, 1969). The age of the Montara Terrace is also disputed but is probably in the range of 200,000 to 300,000 years.

The Half Moon Bay Terrace

The Half Moon Bay terrace is only clearly preserved south of Point Montara. The terrace is only slightly dissected by subsequent stream erosion. Terrace deposits consist of reworked material from the Montara Terrace. The Half Moon Bay marine terrace is likely equivalent in age to the Highway 1 terrace on Ben Lomond Mountain described by Weber and Allwardt (2001) that has a disputed age in the range of 50,000 to 150,000 years.

Stop 11—James V. Fitzgerald Marine Preserve

Stop highlights: Seal Cove Fault, San Gregorio Fault system, syncline, Purisima Formation, fossils, tide pools

The tide pools at the James V. Fitzgerald Marine Preserve are an extremely popular destination for field trips, and for good reason. The preserve is one of the closest tide pool areas to the San Francisco and other Bay Area cities. Steeply dipping, folded rock layers are exposed on a broad wave-cut bench. At low tide, an extensive network of tidal channels and pool areas are exposed. Because of the popularity of this destination, the area is highly protected. Please read the preserve's rules to help reduce impact on the fragile tide-pool environment. Collecting of any kind of natural materials is prohibited. Rangers and volunteer naturalists are usually available for assistance. It is advisable to bring a wildlife field guide, such as the *Audubon Guide to Seashore Creatures* or the *Audubon Guide to California,* to help enjoy wildlife observation. The tide pools contain a diverse fauna including seaweed, crabs,

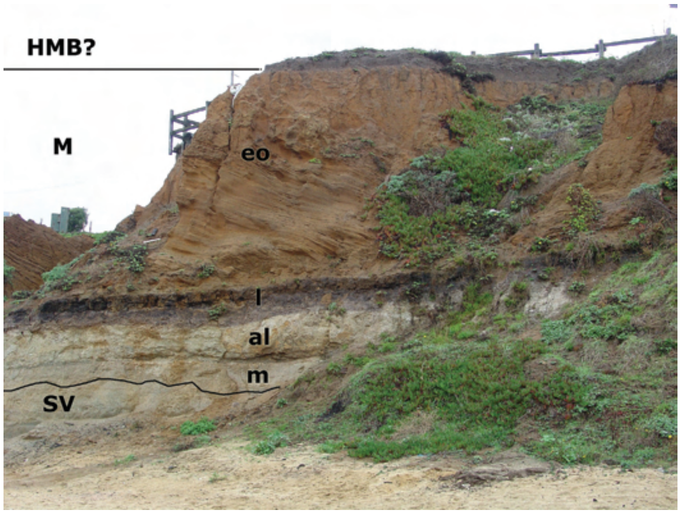


Figure 8-22. Quaternary terrace deposits are exposed in the beach cliff below the Montara State Beach parking area. San Vicente marine terrace deposits (SV) are unconformably overlain by the Montara terrace deposits (M). The Montara terrace deposits consist of a thin lower marine gravel layer (m), a layer of alluvial channel gravels (al), a lignite [coastal swamp] layer (l), and cross-bedded eolian dune sand (eo). Whether the upper surface along Highway 1 is the Half Moon Bay terrace (HMB?) is unclear. This is unlike the Ben Lomond Mountain area, where Marine terraces grow progressively older higher on the mountain. At Montara Beach, the marine terrace deposits are stacked on top of each other. To the south at Ben Lomond Mountain the land has been rising, but at Montara State Beach the land has been relatively stationary relative to sea level.

urchins, sea anemones, mollusks, starfish, fish, and other shelled and soft-bodied invertebrates.

The James V. Fitzgerald Marine Preserve is also a special geologic preserve. The Seal Cove Fault, considered by many geologists to be a strand of the greater San Gregorio Fault system, crosses the shoreline in the preserve at Moss Beach. The fault cuts through sedimentary rocks of the Purisima Formation of late Miocene to Pliocene age. The fault goes offshore just south of the parking area on California Avenue. Unfortunately, the fault is covered by rip-rap on the cliff and cannot be seen. Bathymetry shows a submerged ridge bounded on the northeast by the Seal Cove Fault. The submerged ridge extends northward along the coast for about 2 miles (3.2 km) north of Moss Beach.

In the tide pool area north of the Seal Cove Fault, the Purisima Formation consists of greenish gray sandstone, marl, mudrock, and some conglomeratic beds. The beds are only accessible during low tide; they locally contain an abundance of fossil mollusk shells, mostly large clams. Powell (1998; 2003) suggests that the layered rock units of the Purisima Formation north of the fault were deposited in intertidal depths to about 33 feet (10 m) and the rocks are about 2 to 4 million years old (Pliocene) based on a comparison with modern species. South of the fault, the rock formation has a more massive character and shell fossils are not as abundant. The rocks on the southwest side of the fault are part of an older unit within the Purisima Formation and were probably deposited in subtidal water depths of about 300 to 2,300 feet (100 to 700 m). Bones of marine mammals, microfossils, and rare invertebrate remains have been recovered from this portion of the Purisima Formation. They are older than the rocks to the north, but in the range of 3 to 5 million years.

Ongoing tectonic activity associated with the Seal Cove (San Gregorio) Fault system is responsible for the Moss Beach Syncline, a large fold that is exposed at low tide (fig. 8-23). Deposits of the Half Moon Bay Terrace are also exposed along the sea cliffs at Moss Beach (with an age of roughly 125,000 years). These elevated marine terrace deposits unconformably overlie the Purisima Formation. Boulders in the basal unit of the marine terrace display boring from marine pelecypods (*Pholad*). Look for fault offsets in the marine terrace deposits.

Stop 12—Seal Cove Fault Near the Half Moon Bay Airport (rolling stop)

Stop highlights: Fault scarp, offset Quaternary marine terrace, San Gregorio Fault system

The Seal Cove Fault is considered by many geologists to be an onshore strand of the greater San Gregorio Fault system. Many questions remain unresolved about the San Gregorio Fault system; it is one of the least understood major fault systems in California, partly because so little of it is exposed onshore. Geophysical and oceanographic data suggest it is part of the greater fault system that bounds the western margin of the Salinian Block (see fig. 8-20). The San Gregorio Fault system extends for about 143 miles (230 km) from the Big Sur region south of Monterey Bay and northward to where it merges with the San Andreas Fault system near Bolinas Bay north of San Francisco. Strands of the fault come onshore only in San Mateo County between Año Nuevo and Pescadero and again between Pillar Point and Moss Beach (the latter is the Seal Cove Fault). Like the San Andreas Fault, the San Gregorio Fault displays significant late Quaternary offset. Based on geologic and geophysical evidence, total right-lateral offset along the fault from late Miocene time to the present is estimated between about 70 miles (115 km) (Graham and Dickenson, 1978) and 100 miles (156 km) (Clark and others, 1984). Paleoseismicity studies show that the fault is still active. Trench studies along the Seal Cove Fault show that displacements of between 10 to 16 feet (3 and 5 m) occurred in the pre-Colonial era (sometime between A.D. 1270 and 1775). These fault ruptures probably produced earthquakes of magnitude 7 or greater (Simpson and others, 1997).

Continuing activity along the Seal Cove Fault is ominously revealed by a fault scarp that offsets the young Half Moon Bay Terrace near the Half Moon Bay Airport (fig. 8-24). The elevation of the airport runway is about 40 feet (12 m), whereas the high point west of the fault scarp is about 175 feet (53 m) (fig. 8-25). The Half Moon Bay marine terrace formed when coastal erosion cut a broad bench during a Late Quaternary marine transgression. The flat, wave-cut surface of the marine terrace became exposed as sea level fell and the shoreline retreated seaward about 85,000 years ago. The marine terrace has remained exposed as the coastline (and the entire Santa Cruz Mountains) has progressively continued

Figure 8-23. The Moss Beach Syncline, a broad fold, is exposed at low tide in the James V. Fitzgerald Marine Preserve. Folded sedimentary layers of the plunging syncline consist of fossiliferous sandstone and mudrocks of the Purisima Formation (Miocene to Pliocene age). The Seal Cove Fault scarp is associated with a submerged ridge located near where the waves break just offshore of the syncline.

Figure 8-24. Scarp of the Seal Cove Fault, a strand of the San Gregorio Fault System, forms a linear ridge along the west side of the Half Moon Bay Airport.

to rise. The Half Moon Bay marine terrace is actually folded into a northwest trending, gently-plunging syncline (Lajoie, 1986). Since the marine terrace became exposed, the vertical component of offset along the Sea Cove Fault has produced the 140 foot high scarp (43 m) that is visible today. The fault places latest Quaternary deposits adjacent to Pliocene-age marine mudstones of the Purisima Formation. Note that the rate of horizontal slip on the fault is probably ten to twenty times as great compared to the vertical offset during the same time period.

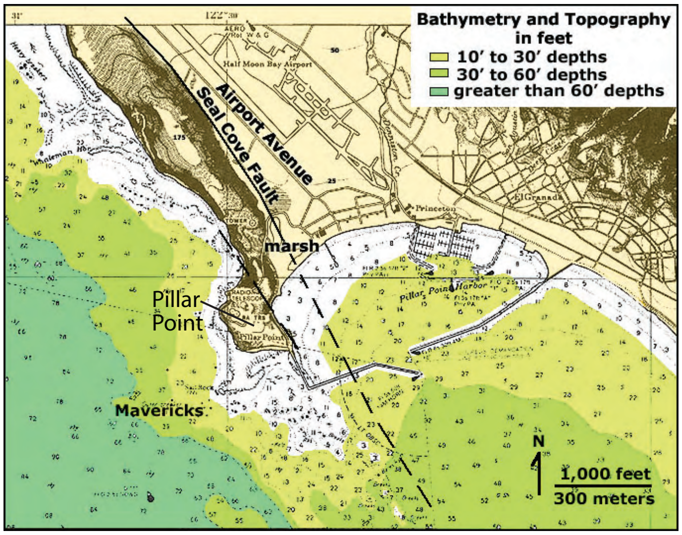


Figure 8-25. Bathymetry and topography along the Seal Cove Fault at Half Moon Bay. The Seal Cove Fault runs along the east side of a linear ridge along the coast between Moss Beach to the north (not shown) and near Pillar Point to the south. Rolling stop 12 is along Airport Avenue, and the parking area for stop 13 is located near the marsh label on the map. The map base is modified from National Oceanic and Atmospheric Administration (NOAA) Chart 18682.

Stop 13—Pillar Point and Mavericks

Stop highlights: Offset marine terrace, San Gregorio Fault system, small faults in sea cliffs, the geology associated with surfing large waves at Mavericks

Pillar Point is a headlands promontory that juts seaward at the west end of Half Moon Bay Harbor. A coastal access trail begins at a parking area next to Pillar Point Marsh. The trail provides access to an extensive wave-cut bench with tide pools that extend seaward of the Pillar Point headlands. The marsh and the tide pool area are part of the James V. Fitgerald Marine Preserve. The marsh itself is part of a pull-apart basin (sag) associated with the Seal Cove Fault (labeled “marsh” on fig. 8-25). The marsh is a famous bird-watching locality, especially during migration periods. **Warning! Do not attempt to climb around the point beyond the end of the trail during high tide, high wave action, or inclement weather!**

The sea cliffs at Pillar Point consist of sand and mudstone of the lower Purisima Formation (late Miocene to Pliocene age). Rare fossils, mostly mollusks and marine mammal bone, have been observed in the rock (Powell, 1998, 2003). Pillar Point proper lies west of a fault that runs parallel approximately 1500 feet (450 m) to the southwest of the Seal Cove Fault. Other small faults that offset sandstone beds are exposed in the sea cliffs along the trail and around the point (fig. 8-26). Seaward of Pillar Point, a broad wave-cut platform and submerged rock reef extends seaward. A break in slope roughly follows the 10 fathom (60 feet; 18 m) contour offshore (fig. 8-25). This rock reef extends offshore nearly a mile on the south side of the point. The high-wave belt, known in the surfing world as “Mavericks,” is located along this westward-extending submerged promontory (fig. 8-25).

Figure 8-26. Sea cliffs on the south side of Pillar Point consist of mudstone and sandstone of the lower Purisima Formation. A high angle reverse fault in the middle of this image offsets a massive sandstone layer by about 10 feet (3 m).

Mavericks is considered one of the most challenging surfing areas of the world, and professional surfers fly in from around the world to attempt to catch monster waves that frequently develop along the outer reef track area offshore of Pillar Point (labeled "Mavericks" on fig. 8-25). Typically several times a year, large weather systems in the northern Pacific Ocean create large wave trains that propagate across the ocean. Buoy and weather satellite data are used to make predictions as to when large wave conditions may occur, giving surfers and the watchful media time to gather at Pillar Point to catch the action. During high seas, waves in the 20- to 30-foot range (6 to 9 m) are not uncommon, and waves in the 40-foot (12 m) and higher range occur on rare occasions. Local legend tells that waves as high as 100 feet (30 m) have been observed. Other hazards to surfing at Mavericks, in addition to at least one documented shark attack, are large rocks exposed along the reef or just below the surface where waves curl and crash, or in the chaotic surf shoreward of Mavericks. Although, surfers traditionally will paddle out to catch waves, many professional surfers attempt the higher and most dangerous waves only by being towed into harm's way behind a jet ski. However, despite the danger, very few people have been killed or severely injured at Mavericks. It is difficult to see surfers in action in the high waves from the shore. However, many videos and films document the history of surfing at Mavericks.

Selected References

Andersen, D.W., Sarna-Wojcicki, A.M., and Sedlock, R.L., 2001, San Andreas Fault and coastal geology from Half Moon Bay to Fort Funston—crustal motion, climate change, and human activity, *in* Stoffer, P.W. and Gordon, L.C. eds., Geology and natural history of the San Francisco Bay Area—a field-trip guidebook: U.S. Geological Survey Bulletin 2188, p. 87-103 [http://geopubs.wr.usgs.gov/bulletin/b2188/].

Brabb, E.E., Graymer, R.W. and Jones, D.L., 1998, Geology of the Onshore Part of San Mateo County, California; derived from the digital database: U.S. Geological Survey Open-File Report 98-137 [http://pubs.usgs.gov/of/1998/of98-137/].

Bryant, W.A. and Cluett, S.E., compilers, 1999, Fault number 60a, San Gregorio Fault Zone, San Gregorio section: Quaternary fault and fold database of the United States: U.S. Geological Survey Open-File Report 03-417 [http://qfaults.cr.usgs.gov/].

Clark, J.C., Brabb, E.E., Greene, H.G., and Ross, D.C., 1984, Geology of the Point Reyes Peninsula and implications for San Gregorio Fault history, *in* Crouch, J.K. and Bachman, S.B., eds., Tectonics and sedimentation along the California margin: Society of Economic Paleontologists and Mineralogists, Pacific Section , Book 38, p. 67-86.

Clifton, H.E. and Hunter, R.E., 1987, The Merced Formation and related beds; a mile-thick succession of late Cenozoic coastal and shelf deposits in the sea cliffs of San Francisco, California, *in* Mason L. Hill, ed., Geological Society of America Centennial Field Guide—Cordilleran Section, Boulder, Colorado, Geological Society of America, v. 6, p. 257-262.

Darrow, R.L., 1963, Age and structural relationships of the Franciscan Formation in the Montara Mountain Quadrangle, San Mateo County, California: California Division of Mines and Geology Special Report 78, 23 p.

Elder, W.P., 2001, Geology of the Golden Gate Headlands, *in* Stoffer, P.W. and Gordon, L.C. eds., Geology and natural history of the San Francisco Bay Area—a field-trip guidebook: U.S. Geological Survey Bulletin 2188, p. 61-86 [http://geopubs.wr.usgs.gov/bulletin/b2188/].

Fruh-Green, G.L., Kelley, D.S., Bermasconi, S.M., Karson, J.A., Ludwid, K.A., Butterfield, D.A., Boschi, C., and Proskurowski, G., 2003, 30,000 years of hydrothermal activity at the Lost City Vent Field: Science, v. 301, p. 495-498.

Graham, S.A., and Dickinson, W.R., 1978, Apparent offsets of on-land geologic features across the San Gregorio-Hogsri fault zone, *in* Silver, E.A., and Normark, W.R., eds., San Gregorio-Hosgri Fault Zone, California: California Division of Mines and Geology Special Report 137, p. 13-23.

Hall, N.T., Wright, R.H., and Clahan, K.B., 1995, Final technical report; paleoseismic investigations of the San Andreas Fault on the San Francisco Peninsula, California: report prepared by Geomatrix Consultants for the U.S. Geological Survey National Hazards Reduction Program, Award No. 14-08-0001-G2081 [http://quake.wr.usgs.gov/prepare/ncep/andreas.html].

Hall, N.T., Wright, R.H., and Clahan, K.B., 1999, Paleoseismic studies of the San Francisco Peninsula segment of the San Andreas Fault Zone near Woodside, California: Journal of Geophysical Research, v. 104, p. 23215-23236.

Jachens, R.C., Wentworth, C.M., and McLaughlin, R.J., 1998, Pre-San Andreas location of the Gualala Block inferred from magnetic and gravity anomalies, *in* Elder, W.P., ed., Geology and tectonics of the Gualala Block, Northern California: Society of Economic Paleontologists and Mineralogists, Pacific Section, Book 84, p. 27-63.

Jack, R.M., 1969, Quaternary Sediments at Montara, San Mateo County, California: University of California, Berkeley, Masters thesis, 131 p.

Kistler, R.W., and Champion, D.E., 1997, Granitoid intrusive suite in the Salinian composite terrane of coastal California: Geological Society of America Abstracts With Programs, v. 29, no. 6, p. 68.

Koehler, R.D., Simpson, G.D., Witter, R., Hemphill-Haley E., and Lettis, W.R., 2002, Paleoseismic investigation of the northern San Gregorio Fault at Pillar Point Marsh near Half Moon Bay, California: U.S. Geological Survey, National Earthquake Hazards Research Program (NEHRP) External Grant Award No. 02HQPA0001, 6 p. [http://erp-web.er.usgs.gov/reports/annsum/vol44/nc/02hqpa0001.pdf].

Lajoie, K., 1986, Coastal tectonics, *in* Wallace, R.E., and Roberts, J.W., Active Tectonics: Washington, National Academy Press, p. 95-124.

Lawson, A.C., 1895a, Sketch of the geology of the San Francisco Peninsula, California: U.S. Geological Survey, Annual Report, v. 15, p. 399-476.

Lawson, A.C., 1895b, A contribution to the geology of the Coast Ranges: American Geologist, p. 342-356.

Lawson, 1914, Geologic Description of the San Francisco district—Tamalpais, San Francisco, Concord, San Mateo, and Hayward quadrangles: U.S. Geological Survey Geological Atlas, Folio 193, scale 1:62,500.

Mattinson, J.M., 1990, Petrogenesis and evolution of the Salinian magmatic arc, *in* Anderson, J.L. ed., The nature and origin of Cordilleran magmatism: Boulder, Colorado: Geological Society of America Memoir 174, p. 237-250.

McLaughlin, R.J., Sliter, W.V., Sorg, D.H., Russell, P.C., Sarna-Wojcicki, A.M., 1996, Large-scale right-slip displacement on the East San Francisco Bay region fault system, California; implications for location of late Miocene to Pliocene Pacific Plate boundary: Tectonics, v.15, no.1, p.1-18.

McLaughlin, R.J., Clark, J.C., Brabb, E.E., Helley, E.J., and Colon, C.J., 2002, Geologic maps and structure sections of the southwestern Santa Clara Valley and southern Santa Cruz Mountains, Santa Clara and Santa Cruz Counties, California: U.S. Geological Survey Miscellaneous Field Studies 2373, 5 sheets, scale 1:24,000 [http://geopubs.wr.usgs.gov/map-mf/mf2373/].

National Audubon Society, 1998, Field guide to California: New York: Alfred A. Knopf, Inc., 447 p.

National Audubon Society, 1981, Field guide to North American seashore creatures: New York: Alfred A. Knopf, Inc., 813 p.

Nilsen, T.H. and Yount, J.C., 1987, Paleocene turbidites and modern landslides of the Point San Pedro-Devil's Slide area, San Mateo County, California, *in* Hill, M.L., ed., Geological Society of America Centennial Field Guide—Cordilleran Section, Boulder, Colorado: Geological Society of America, v. 6, p. 251-256.

Pampeyan, E.H., 1994, Geologic Map of the Montara Mountain and San Mateo 7-1/2' Quadrangles, San Mateo County, California: U.S. Geological Survey Miscellaneous Investigation Series Map I-2390, Scale 1:24,000.

Powell, C.L., II, 1998, The Purisima Formation and related rocks (Upper Miocene-Pliocene), greater San Francisco Bay Area, central California—Review of literature and USGS collection [now housed at the Museum of Paleontology], University of California, Berkeley: U.S. Geological Survey Open-File Report 98-594, 101 p. [http://wrgis.wr.usgs.gov/open-file/of98-594/].

Powell, C.L, II, 2003, Fossils in the San Francisco Bay region, Fitgerald Marine Preserve, San Mateo County: http://wrgis.wr.usgs.gov/wgmt/sfbay/FitzFossil.pdf.

Ross, D.C., 1983, The Salinian Block—a structurally displaced granitic block in the California Coast Ranges, *in* Roddick, J.A. ed., Circum-Pacific plutonic terranes: Boulder, Colorado: Geological Society of America Memoir 159, p. 255-264.

Schroeder, T., John, B., and Frost, B.R., 2002, Geologic implications of seawater circulation through peridotite exposed at slow-spreading mid-ocean ridges: Geology, v. 30, no. 4, p. 367-370.

Simpson, G.D., Thompson, S.C., Noller, S., and Lettis, W.R., 1997, The northern San Gregorio Fault Zone; evidence for timing of late Holocene earthquakes near Seal Cove, California: Bulletin of the Seismological Society of America, v. 87, no. 5, p. 1158-1170.

Tarduno, J.A., McWilliams, M., Debiche, M.G., Sliter, W.V., Blake, Jr., M.C., 1985, Franciscan Complex Calera limestones—accreted remnants of Farallon Plate oceanic plateaus: Nature, v. 317, p.345-347.

Wallace, R.E., 1990. Geomorphic expression, *in* Wallace, R.E., ed., The San Andreas Fault system, california: U.S. Geological Survey Professional Paper 1515, p. 15-58 [http://education.usgs.gov/california/pp1515].

Wahrhaftig, C. and Murchey, B., 1987, Marin Headlands, California: 100-million-year record of sea floor transport and accretion, *in* Hill, M.L., ed., Geological Society of America Centennial Field Guide—Cordilleran Section, Boulder, Colorado: Geological Society of America, v. 6, p. 263-268.

Weber, G.E. and Allwardt, A.O., 2001, The geology from Santa Cruz to Point Año Nuevo—the San Gregorio Fault Zone and Pleistocene marine terraces, *in* Stoffer, P.W. and Gordon, L.C. eds., Geology and natural history of the San Francisco Bay Area—a field-trip guidebook: U.S. Geological Survey Bulletin 2188, p. 1-32.

Williams, J.W., 2001., Elements of engineering geology on the San Francisco Peninsula—challenges when dynamic geology and society's transportation web intersect, *in* Stoffer, P.W. and Gordon, L.C. eds., Geology and natural history of the San Francisco Bay Area—a field-trip guidebook: U.S. Geological Survey Bulletin 2188, p. 105-144 [http://geopubs.wr.usgs.gov/bulletin/b2188/].

Wright, R.H., Clahan, K.B., and Hall, N.T., 1996, Paleoseismic investigations of the San Andreas Fault Zone, Old Canada Road Site, San Mateo County California: USGS Paleoseismic investigations of the San Andreas Fault Zone, USGS Award No: 1434-HQ-97-GR-03167, 5 p. [http://erp-web.er.usgs.gov/reports/annsum/vol40/nc/g3167.htm].

9. Field-trip Guide to Point Reyes National Seashore and Vicinity—A Guide to the San Andreas Fault Zone and the Point Reyes Peninsula

Trip highlights: San Andreas Fault, San Gregorio Fault, Point Reyes, Olema Valley, Tomales Bay, Bolinas Lagoon, Drakes Bay, Salinian granitic rocks, Franciscan Complex, Tertiary sedimentary rocks, headlands, sea cliffs, beaches, coastal dunes, Kehoe Beach, Duxbury Reef, coastal prairie and maritime scrublands

Point Reyes National Seashore is an ideal destination for field trips to examine the geology and natural history of the San Andreas Fault Zone and the northern California coast. The San Andreas Fault Zone crosses the Point Reyes Peninsula between Bolinas Lagoon in the south and Tomales Bay in the north. The map below shows 14 selected field-trip destinations where the bedrock, geologic structures, and landscape features can be examined (fig. 9-1). Geologic stops highlight the significance of the San Andreas and San Gregorio Faults in the geologic history of the Point Reyes Peninsula. Historical information about the peninsula is also presented, including descriptions of the aftermath of the Great San Francisco earthquake of 1906.

Planning Your Trip

The Bear Valley Visitor Center (Park Headquarters) near Olema is about an hour drive north of the Golden Gate Bridge. Point Reyes is located approximately 35 miles north of San Francisco on Highway 1. The park is accessible from San Rafael by Sir Francis Drake Boulevard or from Lucas Valley Road (the latter is discussed in the road log presented below). Although a trip to Point Reyes from anywhere in the Bay Area can be accomplished on a long day, field-trip planners should consider spending a night camping or utilizing overnight accommodations either inside or near the park to have more time to enjoy the experience. However, there is no car camping in the park. Call the Bear Valley Visitor Center well in advance to inquire about group overnight accommodations. It is advisable to check weather forecasts and tide conditions before traveling to Point Reyes. The weather can be very windy and cold along the coast, particularly near the lighthouse on the Point Reyes headlands. More information can be found on the Point Reyes National Seashore website at http://www.nps.gov/pore/.

The park is open daily from sunrise to sunset throughout the year. The Bear Valley Visitor Center is open weekdays, 9:00 a.m. to 5:00 p.m., weekends and holidays 8:00 a.m. to 5:00 p.m.; the Lighthouse Visitor Center is open Thursday through Monday, 10:00 a.m. to 4:30 p.m. Lighthouse stairs and exhibits (weather permitting) are accessible 10:00 a.m.

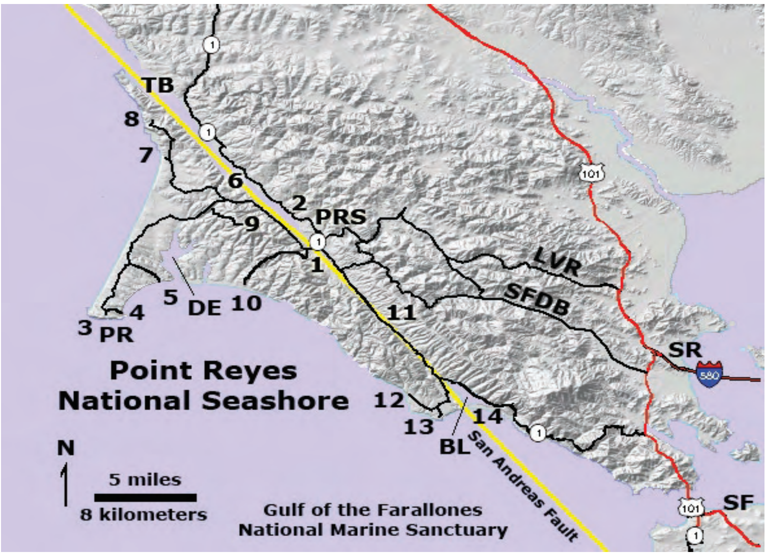


Figure 9-1. Map of the Point Reyes National Seashore area. Numbered stops include (1) Visitor Center and Earthquake Trail, (2) Tomales Bay Trail, (3) Point Reyes Lighthouse, (4) Chimney Rock area, (5) Drakes Beach, (6) Tomales Bay State Park, (7) Kehoe Beach, (8) McClures Beach, (9) Mount Vision on Inverness Ridge, (10) Limantour Beach, (11) Olema Valley, (12) Palomarin Beach, (13) Duxbury Reef, and (14) Bolinas Lagoon/Stinson Beach area. Features include Point Reyes headlands (PR), Tomales Bay (TB), Drakes Estero (DE), Bolinas Lagoon (BL), Point Reyes Station (PRS), San Rafael (SR), and San Francisco (SF), Lucas Valley Road (LVR), and Sir Francis Drake Boulevard (SFDB).

to 4:30 p.m., and the Lens Room is open as weather and staffing permit. All Lighthouse facilities are closed Tuesdays and Wednesdays; Ken Patrick Visitor Center, weekends and holidays, 10:00 a.m. to 5:00 p.m. On weekends during whale watching season (December to April) the road to Point Reyes is closed to private vehicles, but shuttle bus transport is provided.

Geology of Point Reyes—An Overview

Point Reyes National Seashore is an exceptional geologic observatory for many reasons, but it is perhaps most notable for its association with the San Andreas Fault Zone and Great San Francisco earthquake of 1906. The San Andreas Fault Zone is a dividing line between rocks of disparate origin and represents the classic boundary between the North American and Pacific Plates—with the Point Reyes Peninsula residing on the Pacific Plate and the rest of Marin County being part of the North American Plate. Olema Valley and the submerged valleys flooded by Tomales Bay and Bolinas Lagoon are part of the San Andreas Rift Valley (fig. 9-2).

Rocks on the east side of the fault are those of Franciscan Complex, a mix of oceanic crustal rocks that formed in late Mesozoic time (Jurassic and Cretaceous) and were gradually accreted onto the North American continental margin by plate-tectonic motion. Bolinas Ridge along the east side of the rift valley consists mostly of sandstone and metasandstone of

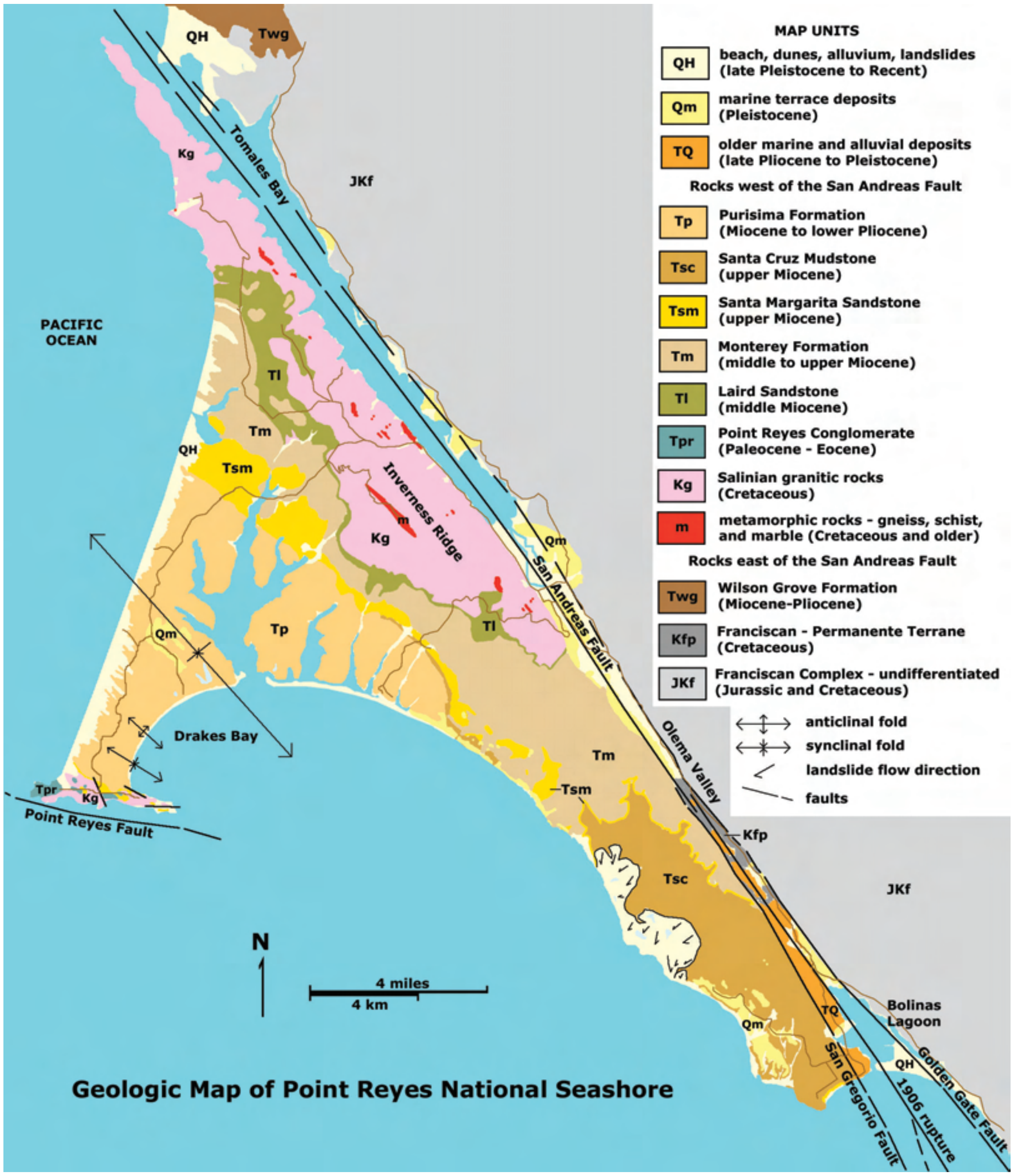


Figure 9-2. Generalized geologic map of Point Reyes National Seashore after Clark and Brabb (1997), Blake and others (2000), and Bruns and others (2002).

Cretaceous age. Pillow basalts are exposed along the highway near Nicasio Reservoir. The pillow basalts formed on submarine volcanoes associated with ancient spreading centers in the Pacific Ocean basin. Basalt that has been altered to greenstone crops out along Highway 1 south of Bolinas. Other rocks in the Franciscan Complex exposed along Highway 1 include chert, shale, and argillite; they represent rocks that formed from sediments that accumulated in mid-ocean to outer-continental-margin environments. Serpentinite occurs in scattered outcrops along the highway and throughout the Mount Tamalpais area. Serpentinite is a mineralogically complex rock of ultramafic composition (rich in magnesium and iron). Serpentinite is derived from rocks that originally crystallized deep in the ocean crust or mantle before undergoing physical and chemical alteration during migration to the surface. A sliver of Franciscan rocks that contain limestone (the Calera Limestone of the Permanente Terrane) occurs within the San Andreas Fault Zone in Olema Valley. The limestone accumulated as limey sediments on the crest of a submarine volcano or plateau.

Point Reyes Peninsula is an elevated block of ancient crystalline basement with a sedimentary cover of Tertiary sedimentary rocks and some Quaternary marine terrace, alluvial, and dune deposits (fig. 9-2). The crystalline basement consists of Cretaceous granitic rocks and some ancient metamorphic rocks (schist, gneiss, and marble). These rocks are called Salinian Complex, named for an extensive belt of granitic and crystalline metamorphic rocks exposed in the Salinas Valley region. However, the name Sur Series also applies because the basement rocks of Point Reyes are closely associated with equivalent crystalline basement rocks exposed along the Big Sur coast south of Monterey. Salinian crystalline rocks are exposed along the crest of Inverness Ridge and in the Point Reyes headlands. In the Point Reyes headlands, a thick sequence of conglomerate and sandstone of Paleocene age rests nonconformably on the Salinian granitic basement. The granitic basement and conglomerate are in turn are unconformably overlain by sedimentary formations of middle Miocene age. Along Inverness Ridge, middle Miocene marine sedimentary rocks (Laird Sandstone and Monterey Formation) rest directly on crystalline basement (the Point Reyes Conglomerate is not present). A sequence of late Miocene and Pliocene formations (Santa Margarita Sandstone, Santa Cruz Mudstone, and Purisima Formation) rests unconformable on top of the Monterey Formation. The Miocene and Pliocene sedimentary rock formations are folded into a broad syncline with a northwest-trending axis. The trough of the syncline is between Inverness Ridge and Point Reyes (see fig. 9-2).

Three separate faults merge near Bolinas Lagoon and in the southern Olema Valley to form the San Andreas Fault Zone at Point Reyes–the Golden Gate Fault, San Andreas Fault, and San Gregorio Fault (Bruns and others, 2002) (see fig. 9-2). These faults extend south through the Gulf of the Farralones. The Golden Gate Fault runs along the eastern shore of Bolinas Lagoon and crosses the Gulf west of the Golden Gate before running onshore in the vicinity of Lake Merced in San Francisco. The North Coast segment of the San Andreas Fault is the trace that ruptured in the 1906 earthquake. It comes onshore near the east end of Stinson Beach. The San Andreas extends southward beneath the Gulf and comes onshore in the vicinity of Mussel Rock in Daly City. The northern extension of the San Gregorio Fault extends onshore in between the town of Bolinas and Duxbury Point on the southern end of the Point Reyes Peninsula. To the south, the San Gregorio Fault runs along the San Mateo Coast and extends across Monterey Bay. These three faults merge into a narrow (less than a mile) fault zone that extends northward through Olema Valley and under Tomales Bay. A large thrust fault, the Point Reyes Fault, runs offshore near the Point Reyes Headlands and is probably responsible for ongoing uplift of the headlands region. All of these faults show signs of tectonic activity extending from late Miocene time to the present.

The composition and characteristics of the Salinian basement and Paleocene conglomerate suggests that the Point Reyes Peninsula actually migrated northward along the San Gregorio Fault system to its present location. Salinian granitic rocks and Paleocene conglomerate on the Monterey Peninsula at Point Lobos are nearly identical to the rocks on Point Reyes. In addition, the late Miocene- to Pliocene-age sedimentary sequence (Santa Margarita Sandstone, Santa Cruz Mudstone, and Purisima Formation) are essentially identical to the same stratigraphic sequence on the east side of the San Gregorio Fault in Santa Cruz County.

Elevated marine terraces along with ancient alluvial and coastal-dune deposits suggest that the Point Reyes Peninsula has been rising throughout the Quaternary Period. However, ongoing sea-level rise associated with the melting of extensive ice-age continental glaciers is responsible for the flooding and subsequent Holocene sediment filling of ancient valleys beneath Tomales Bay, Drakes Estero, and Bolinas Lagoon. Coastal processes associated with the gradual sea-level rise following the last ice age are responsible for the erosional development of the sea cliffs and headlands and the accumulation of sediments on ocean beaches and dunes, as well as the back filling of baylands and lagoons throughout the peninsula.

Cultural History of the Point Reyes Region

[Summarized after Gilliam (1962), Caughman and Ginsberg (1987), and from National Park Service sources.]

We don't know when humans first arrived on the Point Reyes Peninsula. Archeological studies report human activity in California extending back to near the end of the Pleistocene Epoch, nearly 11,000 years ago. The record of early human history in the region has probably been lost to the nearly 400 foot (120 m) rise in sea level since the final maximum of the Wisconsin glaciation about 18,000 years ago. At that time, the shoreline was about 30 miles (50 km) west of its present location, and the Point Reyes Peninsula was part of a system of low inland hills. Archeological evidence indicates that for at least the past several thousand years people have utilized the peninsula. When Europeans arrived in the region, the Coast Miwok

Indians lived in villages along the bays; they hunted, fished, and gathered food and living supplies from the region's abundant wildlife and natural resources. The Miwok people were probably descendents of earlier cultures in the region.

Historians still debate whether Sir Francis Drake stopped at Point Reyes. Drake was an English pirate and explorer serving Queen Elizabeth I. Drake had a ship, the *Golden Hind*, loaded with stolen Spanish treasure taken from settlements in the New World on his voyage north from Cape Horn. Facing the prospects of revenge by Spanish galleons, he choose not to spend more time seeking a fabled Northwest Passage but rather to sail west across the Pacific Ocean to return to England. Before heading west, Drake returned south along the California coast seeking a location to repair and resupply his ship before the long journey home. Journals from Drake's adventurous voyage (1577 to 1580) described landing at a location with white cliffs, similar to the White Cliffs of Dover. In 1579, Drake's crew brought the ship onshore to remove barnacles and clean, caulk, repair damage, and gather supplies before the next stage of their voyage. This possibly took place somewhere on one of the sheltered shores of Drakes Estero, inland of Drakes Bay. However, no authenticated artifacts from Drake's voyage have been recovered in the Point Reyes area.

The earliest mention of Point Reyes is in historic records of the 1595 shipwreck of the Spanish galleon, the San Agustin. The ship, captained by Sebastián Rodrígues Cermeño was on her return journey from the Philippines. Despite a damaged ship and a mutinous tone from the crew, Cermeño chose to spend 3 weeks exploring the coast in the vicinity of Point Reyes. However, the ship was probably anchored near the mouth of Drakes Estero when, on a November day, an unexpected storm drove the ship into the coast. Several of the crew members were lost. The remains of the ship and cargo were abandoned. Still following Cermeño's command, the crew modified and crowded into the San Agustin's small launch vessel and heroically paddled nearly 1,500 miles south to Spanish outposts in Mexico. In his exploration, he named the coastal embayment between Point Reyes and Point San Pedro, "La Baya de San Francisco," but never actually sailed through the Golden Gate or visited the land that now bears the name. Chinese Ming pottery from the shipwrecked cargo of the *San Agustin* has been recovered from Miwok Indian village sites. The loss of the San Agustin was perhaps the first of many shipwrecks that have occurred in the treacherous waters around Point Reyes. Point Reyes extends nearly 9 miles (15 km) seaward, perpendicular to the coast. During major coastal storms, many ships driven by strong winds and currents were unable get far enough to the west to get around Point Reyes and ended up trapped and shipwrecked in Drakes Bay.

On a return journey to Spain from Cape Mendicino in 1603, Spanish explorer Sebastián Vizcaíno mistook what is now the entrance to Tomales Bay for the mouth of a great river. He named it "Rio Grande de San Sebastián." On the Roman Catholic holiday of the Three Kings (January 6, 1603), Vizcaíno sighted the headlands and gave the name "La Punta de Los Tres Reyes," and hence the name, Point Reyes. Not until 1793 when another Spaniard, Juan Matute, explored the area, did Vizcaíno's river prove to be a bay. Matute named his new bay "Puerto Nuevo."

The bay and peninsula were home to Miwok Indians who had a settlement along the shore. Both Drake and Vizcaíno reported friendly encounters with the Miwok people who provided supplies for the ships. Unfortunately, like most native California cultures, the Miwok population was decimated by disease, subjugation, and slavery during the era of Mexican colonization. A mission was built in 1817 in what is now San Rafael. During Spanish rule, the Point Reyes Peninsula was divided into land-grant ranchos. However, after the Mexican Revolution of 1821, the San Rafael Mission was secularized, and the few remaining Miwok that escaped or were released from subjugation had lost their land.

After California was ceded to the United States after the Mexican American War of 1848, the Point Reyes Peninsula became the possession of a San Francisco law firm. The peninsula was then subdivided into dozens of dairy and cattle farms. For nearly 75 years, dairy products and cargo from the ranches were loaded onto schooners that docked in Drakes Estero and Tamales Bay and shipped to San Francisco. The Gold Rush brought a wave of immigrant pioneers to the area. Bolinas was a thriving logging town by 1850. Lumber and firewood were loaded at Bolinas Lagoon for shipment to San Francisco. Over time, Bolinas and nearby Stinson Beach grew as a result of tourism and inhabitants who chose to live in the coastal communities and commute to the city. The town of Olema was established in 1859 and for a short period became a commercial center for the peninsula. In the early 1870s, the North Pacific Coast Railroad was built to link the port of Sausalito near the Golden Gate to parts of Marin and Sonoma Counties. From San Rafael, the rail line followed Lagunitas Creek Valley to the south end of Tomales Bay. By 1875, the rail line extended northward along the east side of the bay to the town of Tomales. By 1877, the railroad was extended to serve lumber mills in the Russian River area. In 1883, the town of Point Reyes Station was developed. The new train stop 2 miles north of Olema caused the older established town to fade in significance. While in operation, the railroad transported lumber, farm produce, commuters, and tourists, until the rail line ceased operation in 1933.

Point Reyes National Seashore was authorized for addition to the National Park Service on September 13, 1962. The park now encompasses about 71,000 acres (28,700 hectares), with additional extensive land holdings in the region managed in cooperation with Golden Gate National Recreation Area and California State Parks. The southeastern end of the peninsula is set aside as part of the Philip Burton Wilderness Area and Research Natural Area. The Tule Elk Reserve encompasses the north end of the peninsula including Tomales Point. Much of the western end of the peninsula consists of pastoral lands associated with dairy and cattle ranches that are maintained in cooperation with the National Park Service. The U.S. Coast Guard maintains small stations near Abbotts Lagoon and at Palomarin Beach, and private land holdings encircle the small communities of Bolinas, Olema, and Inverness Park.

Road Log from Golden Bridge to Point Reyes National Seashore's Park Headquarters

Golden Gate Bridge to Bear Valley Visitor Center (Park Headquarters) by Lucas Valley Road

Distance	Description
0 mi (0.0 km)	Golden Gate Bridge Vista Area on Highway 101 (northbound lane at north end of bridge). Restrooms are available at the Vista Area.
3.5 mi (5.6 km)	Pass exit to Highway 1 to Stinson Beach (this is recommended as a return route; it is 31 miles to the Bear Valley Visitor Center/Park Headquarters along Highway 1).
9.0 mi (14.5 km)	Pass Sir Francis Drake Boulevard (this is an optional park access route, but has many more stop lights than Lucas Valley Road).
15.5 mi (24.9 km)	Take the Lucas Valley Road exit from Highway 101. Turn left (west) on Lucas Valley Road.
21.5 mi (34.6 km)	Large outcrops of Franciscan Complex rocks occur along road.
25.2 mi (40.5 km)	The route passes through groves of coast redwoods (*Sequoia sempervirens*).
26.3 mi (42.3 km)	Turn right (north) on Nicasio Valley Road. Nicasio Reservoir is on the left.
26.5 mi (42.6 km)	The road passes the small town of Nicasio.
29.3 mi (47.1 km)	Nicasio Reservoir is on the left. Many Franciscan Complex "knockers" outcrops are in this area.
30.5 mi (49.0 km)	Turn left on Point Reyes-Petaluma Road toward Point Reyes Station.
33.4 mi (53.7 km)	Pillow basalts are exposed in roadside outcrops on the left near a sign for Golden Gate National Recreation Area. These rocks are part of the Nicasio Terrane of the Franciscan Complex.
33.7 mi (54.2 km)	Bear right across a bridge to continue on Point Reyes-Petaluma Road to Point Reyes Station.
36.9 mi (59.4 km)	Turn left on Highway 1 (Shoreline) at Point Reyes Station. The town of Point Reyes Station offers restaurants, gas, and other travel services. Highway 1 (Shoreline) makes a few turns through town. See the discussion and historic photographs of the Point Reyes Station area below. **NOTE:** Optional **Stop 2—Tomales Bay Trail** is located along Highway 1 at 1.7 miles north of Point Reyes Station on the east side of the bay. See the stop 2 discussion below.
37.4 mi (60.2 km)	The historic Point Reyes Station (a brick building) is on the right (see fig. 9-3 below).
37.6 mi (60.5 km)	Turn right on Sir Francis Drake Boulevard just past the bridge over Lagunas Creek.
38.3 mi (61.6	Turn left on Bear Valley Road.
38.7 mi (62.3 km)	Pass Limontour Road on right (see **Stop 10 – Limantour Road** description below).
38.8 mi (62.4 km)	A small dirt road to the left leads to a parking area along the San Andreas Fault. An undeveloped path that starts at the parking area leads to the top of a pressure ridge developed along the fault. The top of the grassy knoll is a good place to view the sag ponds, marshlands, and fault scarps at the south end of Tomales Bay (see fig. 9-7). For the next mile, Bear Valley Road follows the trace of the San Andreas Fault that ruptured in the 1906 earthquake. The road follows and crosses a fault scarp; sag ponds and marsh along Olema Creek are on the right.
40.0 mi (64.3 km)	Turn right into the Bear Valley Visitor Center and Park Headquarters area near the red barn.
40.2 mi (64.7 km)	**Stop 1—Bear Valley Visitor Center and Earthquake Trail** (see description below).

Point Reyes Station and the 1906 Earthquake

Shortly after the 1906 earthquake and fire that destroyed much of San Francisco, reports started arriving about surface ruptures and damage in the Olema Valley and the Tomales Bay-side community of Point Reyes Station. Reporters and earthquake investigators made their way north to document the damage associated with rupture along a fault line that would eventually be known as the San Andreas Fault. Perhaps the most famous pictures from those early investigations include a picture of a toppled train at Point Reyes Station, taken with a borrowed camera by one of train's engineers, and pictures of the fault rupture taken by U.S. Geological Survey geologist Grove Karl Gilbert (1908) (figs. 9-3 to 9-6).

Figure 9-3. A famous historical photograph taken by an engineer of a derailed train that tipped over at the Point Reyes Station during the 1906 earthquake (image from Jordan, 1907). The narrow gauge train was stopped at the station on a section of track that ran roughly parallel to the fault less than a mile east of the rupture. Based on the engineer's description of the rocking motion that fell the locomotive, Anooshehpoor and others (1999) calculated the earthquake motion created ground acceleration that was in the range of 0.7 to 1.1*g* (*g* is the force of gravity).

Stop 1—Bear Valley Visitor Center (Park Headquarters) and Earthquake Trail

Stop highlights: San Andreas Fault scarp, 1906 earthquake rupture, park geology and ecology exhibits

The Point Reyes National Seashore, Bear Valley Visitor Center (Park Headquarters) is located near the towns of Olema, Point Reyes Station, and Inverness, and is near the south end of Tomales Bay (see figs. 9-1 and 9-7). The Visitor Center is the best place to start a field trip in the park. The Visitor Center provides brochures, maps, book sales, and exhibits about the land, wildlife, and the Coast Miwok Indians that inhabited the peninsula before European settlement. It is

Figure 9-4. Photograph by Gilbert (1908) of surface rupture along the fault near Point Reyes Station. The view is looking northwest toward marshlands at the south end of Tomales Bay. The photograph illustrates a classic example of a sidehill bench. Note the extent of timber removal on Inverness Ridge in the distance (top left).

Figure 9-5. View looking southeast along the fault near Point Reyes Station. Note the woman for scale near the top of the hill to the left of the fault scarp.

Figure 9-6. This view of an offset road near Point Reyes Station shows 20 feet (6 m) of horizontal slip caused by the 1906 earthquake. Photograph by Gilbert (1908).

Figure 9-7. This view is looking north from the top of a shutter ridge located along Bear Valley Road about 1.5 miles (2.4 km) north of the Bear Valley Visitor Center. Inverness Ridge is on the left (west). The wetlands of southern Tomales Bay are near the center of the image, and Point Reyes Station is on an elevated terrace to the right (east). A scarp along the main trace of the San Andreas Fault is visible as a vegetation change along a break in slope located just above the parked vehicle on the left.

recommended that you check the Point Reyes National Seashore website and call the Visitor Center before planning a trip to the park.

The Visitor Center is located near the historic 1906 rupture of the San Andreas Fault. Fault rupture and ground failure features in the area around Point Reyes Station and Olema were described and photographed by Grove Karl Gilbert (1908), and by others. Although little physical evidence remains from the great earthquake, the National Park Service maintains a trail to the 1906 fault rupture zone (figs. 9-8 and 9-9). The Earthquake Trail starts in the Visitor Center parking lot. Earthquake Trail guides are available at the Visitor Center. Signs and displays along this 0.5 mile (0.8 km) walk provide basic information about plate tectonics and the geologic setting and history of the San Andreas Fault. A fault scarp is clearly visible along the trail. The fault scarp represents the cumulative effects of slip from many earthquakes over many thousands of years that have occurred along this active strand of the San Andreas Fault; only a small fraction of the vertical relief along the fault scarp is from the 1906 rupture. More features related to earthquake faults can be seen along the Rift Zone Trail. This trail roughly follows the trace of the 1906 rupture from the Visitor Center southward for 4 miles (7 km) to the trailhead at Five Brooks along Highway 1. Paleoseismic studies based on trench excavations by Neimi and Hall (1992) indicate that the slip rate of the 1906 trace (North Coast segment of the San Andreas Fault) averaged about 24(±3) mm per year for the past 2,000 years and that the recurrence interval for large earthquakes is in the range of 221(±40) years.

According to G.K. Gilbert, who recorded the 1906 earthquake's impacts, the only recorded casualty in the Point Reyes region was a cow that was supposedly crushed and killed upon falling into an open fissure during the earthquake. It was later revealed that the cow story was really a hoax perpetrated by a farmer who had dumped a dead cow into an open fissure. The sensational story was widely distributed before it was revealed to be a joke on reporters.

Figure 9-8. A reconstructed historical fence offset by the San Andreas Fault in 1906. This exhibit is along the Earthquake Trail near the Bear Valley Visitor Center. The original fence at this location was offset about 18 feet (5.5 m). As much as 26 feet (8 m) of horizontal surface slip was reported on the fault in the Olema area (Gilbert, 1908).

Figure 9-9. Blue posts mark the trace of the surface rupture of the 1906 earthquake. The Shaffer Ranch barn was built on the trace of the fault and was damaged by the earthquake. This view is looking north from the offset fence exhibit area along the Earthquake Trail.

Stop 2—Tomales Bay Trail (Golden Gate National Recreation Area) (optional)

Stop highlights: San Andreas Rift Valley, Tomales Bay, Franciscan Complex, blueschist knockers, marshland and coastal-prairie habitats

The Tomales Bay Trail is a good optional destination to examine unusual outcrops of Franciscan Complex bedrock in a scenic setting on the east side of Tomales Bay. The Tomales Bay Trail is located 1.7 miles (2.7 km) north of Point Reyes Station along Highway 1 (Shoreline) and is 4.3 miles (7 km) north of the Bear Valley Visitor Center (Stop 1) near Olema.

The Tomales Bay Trail area is located at the north end of a marine terrace that extends southward through the Point Reyes Station area. From the parking area, the trail crosses a low incised plateau-like area (part of the old terrace) before dropping down to the salt marsh at the south end of Tomales Bay. Of geologic interest are outcrops of metamorphosed sandstone which rise above the coastal prairie near the parking area (fig. 9-10). The features are called "blueschist knockers"—blueschist being the grade of metamorphic change that the rock has experienced, imparted to the rock by crystallization of the mineral glaucophane under moderate crustal depth pressure and at relatively low temperature. The word "knocker" is a regional geologic term used to describe lone outcrops of bedrock that rise above the surrounding landscape in areas typically underlain by Franciscan Complex. Over time as erosion has worn down the landscape, resistant blocks of metamorphic sandstone and other rock are left behind as softer, more fractured and weathered material erodes away. Knockers typically occur in areas where bedrock has been heavily sheared and mixed through the ongoing tectonic development of the region, beginning with tectonic forces associated with plate-tectonic transport and subduction, as well as later uplift and shearing along fault zones. The French word *mélange* (meaning mix) is applied to areas of sheared rock in the Franciscan Complex where rock masses are often too small and discordant to be mapped as individual geologic units. Rocks of the Franciscan underlie the countryside east of Tomales Bay.

Also of interest are the elevated marine terraces along Highway 1 along the shores of Tomales Bay (fig. 9-11). These ancient surfaces correspond to periods of time when sea level was higher than at the present. Shoreline erosion and sediment deposition during high-standing sea level associated with interglacial periods of the Pleistocene Epoch resulted in the formation of wave-cut platform and beaches. Later, sea level fell and as the land in many coastal areas continued to rise and these ancient beaches and wave-cut platforms became isolated from shoreline and became elevated marine terraces that we see today. The town of Point Reyes Station is built on a prominent marine terrace that originally formed about 100,000 to 150,000 years ago and is currently about 30 to 50 feet (9 to 15 m) above sea level. These terraces are offset or tilted along the San Andreas Fault and provide useful information to determine the rates of tectonic uplift and erosion affecting the landscape.

Figure 9-10. Large blueschist "knockers" rise above the coastal prairie in low hills along the east shore of Tomales Bay along the Tomales Bay Trail. The blueschist is part of the extensive belt of Franciscan Complex along the east side of the San Andreas Fault in the Point Reyes National Seashore region. Along the eastern shore, salt marsh gives way to coastal prairie grasslands. The grasslands dominate the hillsides east of the bay extending to the top of Bolinas Ridge. To the south and east, grasslands give way to coastal sage scrublands. Farther inland, the hillsides are dominated by oak woodlands, chaparral, and mixed evergreen forest dominated by bay laurel and Douglas fir.

Figure 9-11. View of Tomales Bay and Inverness Ridge from a roadside pull off along Highway 1 about a mile north of the Tomales Bay Trail parking area. Note the contrast of the grassland prairie on the east side of the bay with the mixed evergreen and pine forest on the slopes along the west side of the bay. The vegetation contrast on opposite sides of the bay reflects the different characteristics of the bedrock and soils on opposite sides of the fault zone. The contrast also reflects the difference between the slope, aspect, precipitation, and other climatic factors influencing vegetation on opposite sides of the bay.

Road Log–Bear Valley Visitor Center to the Lighthouse Museum at Point Reyes Headlands

Route highlights: Tomales Bay, Point Reyes Peninsula, Inverness Ridge, Drakes Estero, Drakes Beach, Point Reyes Headlands, Chimney Rock, Point Reyes Lighthouse, Purisima Formation, Monterey Formation, Point Reyes Conglomerate, Cretaceous granitic rocks, marine terrace deposits

The destination of most people visiting Point Reyes National Seashore is probably the Point Reyes Lighthouse area. The road log listed below provides mileages to selected destinations along Sir Francis Drake Boulevard that leads to the lighthouse. The road log begins at the Bear Valley Visitor Center (Park Headquarters) and ends at the parking area for the Point Reyes Lighthouse and Visitor Center (Stop 3). Be sure to check weather conditions at the lighthouse before proceeding (it may be closed due to inclement weather). See discussions below for stop information, other optional routes, or alternative destinations.

Distance	Description
0.0 mi (0.0 km)	**Bear Valley Visitor Center—Park Headquarters (Stop 1)**
1.4 mi (2.6 km)	Pass intersection for Limantour Road; see discussion for **Limantour Road (Stop 10)**.
1.7 mi (2.7 km)	Turn left on Sir Francis Drake Boulevard. The small communities of Inverness Park and Inverness are spread out for several miles along Sir Francis Drake Boulevard north of the intersection with Bear Valley Road. For several miles the road runs through the bayside residential community along the western shore of Tomales Bay. As many as 45 residences were destroyed in the Inverness Park area by the 1995 Vision Fire that burned much of the central Point Reyes Peninsula.
3.7 mi (6.0 km)	Town of Inverness. The parking area behind Inverness Store provides a good view of the bay and an uplifted and tilted marine terrace along the east shore (see figs. 9-12 and 9-13).
6.5 mi (10.5 km)	Intersection of Pierce Point Road on right. Pierce Point Road leads north towards Tomales Point; see discussions for **Tomales Bay State Park (Stop 6), Kehoe Beach (Stop 7),** and **Tomales Point Peninsula (Stop 8)**. The road crosses the crest of Inverness Ridge near this intersection. Bedrock in this area consists of Salinian granitic rocks, but along the ridge they are deeply weathered. Only traces of the weathered granitic rock are exposed along the road.
6.9 mi (11.1 km)	The Laird Sandstone is exposed on the right side of the road near historic M Ranch.
7.6 mi (12.2 km)	Intersection of Mount Vision Road on left. See discussion for **Mount Vision (Stop 9)**.
7.9 mi (12.7 km)	Gently dipping beds of the Monterey Formation are exposed in an old quarry-like cut along the right side the road.
9.5 mi (15.3 km)	A view of Schooner Bay on Drakes Estero is on the left (east). The north end of Schooner Bay is used for oyster farming. Entrance to a U.S. Coast Guard Station is on the right.
10.6 mi (17.1 km)	A large radio transmission and receiving antenna facility on the right was used primarily for ship-to-shore communications in the Pacific region. The Marconi RCA, AT T, and MCI stations are still partly operational, but have more historic significance. Wireless communications began in the Point Reyes area in 1913, but the large Art Deco-design antenna field began operation in 1929 and was used through the WWII Era. Large vegetation-stabilized dunes are visible along the shore west of the antenna field.

Continued.

11.2 mi (18.0 km)	The mouth of Drakes Estero is visible to the left near historic F Ranch. The road continues south and crosses a saddle area on the elevated marine terraces are visible.
13.3 mi (21.4 km)	Point Reyes Beach North access road is on the right (west).
14.5 mi (23.3 km)	Road to **Drakes Beach (Stop 5)** is on the left (east).
15.0 mi (24.1 km)	Pont Reyes Beach South access road is on the right (west).
18.8 mi (30.2 km)	Road to the **Chimney Rock** and the **historic Point Reyes Lifeboat Station (Stop 4)** is on the left (east). Outcrops in the vicinity consist of Point Reyes Conglomerate.
19.8 mi (31.9 km)	**Point Reyes Lighthouse and Visitor Center parking area (Stop 3)**

Stop 3—Point Reyes Lighthouse

Stop highlights: Salinian basement, porphyritic granite, Paleocene-Eocene conglomerate, Point Reyes Fault, San Gregorio Fault system

Point Reyes Lighthouse is the most popular destination in the park. Note that on weekends and holidays during whale watching season the road is closed to private vehicles and it is necessary to shuttle to the lighthouse museum area. Also note that the lighthouse is closed when winds exceed about 40 mph (18 m/sec). It is recommended to call the park in advance.

The weather at Point Reyes ranges from capricious to atrocious. Windy conditions can occur any time of year. The maximum wind speed recorded at the lighthouse was 133 mph (60 m/sec), and wind above 60 mph (27 m/sec) is not uncommon. The point is engulfed in fog an average of about 140 days a year, especially in the summer. However, the annual rainfall at the point averages less than 20 inches per year. Perhaps surprisingly, the average temperature is fairly constant at the lighthouse. The warmest temperatures are late summer (August to September) when the mean daily temperature is about 56° F, whereas the average daily temperature in January is about 50° F (Galloway, 1977).

The Point Reyes Lighthouse was constructed in 1870 on a headland point about 296 feet (90 m) above sea level. Traditional lighthouse operation ended when the Coast Guard installed an automated light and foghorn in 1975. The lighthouse was not built on top of the 600-foot (183 m) summit of Point Reyes because the high point is more often enshrouded in fog. However, on a clear day the view from the lighthouse

Figure 9-12. View of Tomales Bay from the parking area of Inverness Store (in the town of Inverness) along Sir Francis Drake Boulevard. A small sea cliff on the opposite side of the bay (to the left) is at the end of an uplifted marine terrace located near the trace of the San Andreas Fault in Tomales Bay. As a result of folding along the fault zone, the once probably flat marine terrace now dips gently to the east.

Figure 9-13. G.K. Gilbert (1908) took this photograph of a pushed up shoal in the marsh flats along the west shore of Tomales Bay. Gilbert reported stories of tsunamis more than 6 feet (2 m) high along the northeast shore of Tomales Bay caused by the earthquake. Note the large slumps along the east shore of the bay. Gilbert did not report whether these slumps were caused by the 1906 earthquake. However, he described significant landscape changes in the tidal flats as a result of mud shifted by the motion of the earthquake.

extends from the San Mateo coast to the south, to the Farollan Islands to the west, and Tomales Point and beyond to the north. The lighthouse was operated by a lighthouse keeper and usually three assistants. The light operated with a 120,000 candlepower flame lamp focused by a rotating Fresnel lens (later modified with a half-million candlepower electric lamp). The light was operated only from sunset to sunrise. At night, the lighthouse could project to the horizon—a distance of about 24 miles (39 km). At 5:12 am on April 18, 1906, the great earthquake struck and the Fresnel lens shifted off its track. However, the lighthouse keeper was able to make quick repairs so that the light was operational that evening.

The water depth quickly drops to about 150 feet (46 m) within a few hundred feet from shore. The lighthouse observation platform is an excellent location to observe gray whales in migration during January to April. Harbor seals, elephant seals, and sea lions are commonly seen swimming around the point, and occasionally great white sharks are sighted in search of their sea mammal prey. During high seas, crashing waves around the point provide an awesome display.

Uplift along the offshore Point Reyes Fault is likely responsible for the steep topography and bathymetry on the west- and south-facing headlands. Other faults can be observed onshore in the headlands (see fig. 9-2). Outcrops of Point Reyes Conglomerate can be examined along the path and around the Lighthouse Visitor Center (figs. 9-14 to 9-17). Granitic rocks are exposed in the sea cliffs near the parking area and in the Chimney Rock Point area (see Stop 4 below). Clark and Brabb (1997) mapped the granitic rocks as the “Porphyritic granodiorite of Pont Reyes” and published radiometric dating data, suggesting a middle Late Cretaceous age of about 82 million years (see discussions about the other granitic rocks on the Point Reyes Peninsula at stops 6, 7, and 8 below).

Figure 9-15. The Point Reyes Lighthouse was built on a headland promontory of Paleocene conglomerate. The historic lighthouse building is now a museum. The lighthouse observation deck is a good place to observe gray whales as they migrate in January to April. Reaching the lighthouse requires descending and ascending 300 steps. It is frequently foggy and windy at the lighthouse, and the lighthouse is closed during inclement weather.

The Point Reyes Conglomerate is about 700-feet (213 m) thick, but is probably only a fraction of its original thickness. The age of the conglomerate is disputed. Galloway (1977) describes the unit as Paleocene in age, but Clark and Brabb (1997) assign the unit a younger age of Eocene (about 50

Figure 9-14. View of the beach strand north of Point Reyes. Cliffs of Paleocene conglomerate crop out in the headlands in the foreground. Note the extensive belt of coastal dunes in the back beach area. Older dune deposits stabilized by vegetation occur throughout the Point Reyes peninsula. This photograph was taken near the Lighthouse Visitor Center on Point Reyes. The beach extends in a north-northeast direction perpendicular to the prevailing north-northwest wind direction.

Figure 9-16. Outcrops of Paleocene conglomerate and sandstone are well exposed near the Lighthouse Visitor Center. The conglomerate and sandstone represent deep-sea canyon and upper submarine-fan deposits. Large, barren cement surfaces near the Lighthouse Visitor Center were used to trap rainwater for storage in cisterns to supplement the water needs of the lighthouse staff.

million years). Burnham (1998a, 1998b, 1999) demonstrates that the Point Reyes Conglomerate is essentially identical to the Carmelo Formation which crops out at and near Point Lobos south of Monterey. In both locations, the conglomerate is in direct contact with the underlying granitic basement (granodiorite). Distinctive clasts within the conglomerate include pebbles and cobbles of pink to purple porphyry tuff that contain pink crystals of feldspar and clusters of zircon and titanomagnetite grains (fig. 9-17). Burnham obtained radiometric (zircon U/Pb) ages of about 152 million years from conglomerates at Point Reyes and Point Lobos. In addition to these factors, the depositional sedimentary features preserved within the conglomerate suggest that the Point Reyes and Point Lobos deposits accumulated within the same submarine canyon system. Today, the deposits are separated by about 112 miles (180 km), offset by movement on the San Gregorio Fault system.

Clark and others (1984), Clark and Brabb (1997), and Stanley and Lillis (2000) describe the correlation of other units on the Point Reyes Peninsula to equivalent units in the Santa Cruz Mountains. Clark (1984) suggested that stratigraphic relationships within the Monterey Formation indicated that right-lateral slip along San Gregorio Fault was initiated about 10 million years ago. Clark also demonstrated that a glauconitic facies dated at about 8 million years within the Santa Margarita Sandstone crops out in both the Santa Cruz Mountains and the Point Reyes Peninsula. The Santa Margarita glauconitic unit indicates an offset of about 100 km. Although estimates vary, the timing and slip displacement of equivalent units in Point Reyes and along the Santa Cruz Coast indicates that the rate of slip along the San Gregorio Fault was greatest in late Miocene time (about 25 to 30 mm/yr), but has gradually diminished to between about 4 to 10 mm/year (Clark, 1998; Bruns and others, 2002). The diminishing rate of offset along the San Gregorio Fault is likely related to increasing slip accommodation along the other faults on the San Francisco Peninsula and East Bay region.

Figure 9-17. The Point Reyes Conglomerate contains clasts that represent an assortment of different rock types; most are of volcanic origin. The person's finger points to a dark andesitic porphyry (tuff) that contains small, pink feldspar crystals. This striking lithology can be seen in conglomerate beds throughout coastal California extending from Ventura to Point Reyes. The conglomerate and granitic rock at Point Reyes correlates with the Carmelo Formation and Monterey Granodiorite at Point Lobos south of Monterey, California (Burnham, 1999).

Geophysical data demonstrate that fault systems in the San Francisco Peninsula and beneath the Gulf of the Farallones merge together to become the San Andreas Fault Zone in the Point Reyes Peninsula region. This means that the cumulative measurable slip for the San Gregorio, Pilarcitos/Montara, San Andreas, and Golden Gate Faults must also be accommodated by the San Andreas Fault Zone at Point Reyes. The Peninsula segment of the San Andreas Fault displays slip of about 14 miles (22 km) since about 1.8 million years ago; this displacement followed about 65 miles (105 km) of slip that occurred since late Miocene time on the Pilarcitos/Montara Fault system (Jachens and others, 1998). However, the Golden Gate Fault appears not to extend south of Lake Merced on the San Francisco Peninsula, so fault motion along the Golden Gate Fault near Point Reyes must be step over from the San Andreas and the other faults south of Bolinas. Using the combined offset of the San Gregorio, Pilarcitos, and San Andreas Faults on the San Francisco Peninsula, the total slip along the San Andreas Fault Zone on the Point Reyes Peninsula is estimated to be more than about 185 miles (300 km) since late Miocene time. As an independent line of evidence, the cumulative amount of post-early Miocene slip on the San Andreas Fault is about 196 miles (315 km) of right-lateral slip based on correlation of the Neenach Volcanic Formation in the western Mojave region with the Pinnacles Volcanic Area south of the Bay Area (Sims, 1993). However, studies of correlation of Cretaceous plutonic rocks, and Paleocene and Eocene sedimentary rock indicate that rocks on the Northern California Coast, including Point Reyes, have experienced additional northward displacement on fault systems that predate the San Andreas Fault system (Brabb and others, 1998; Wentworth and others, 1998). The granitic basement at Point Reyes originally formed as part of a long, north-south Cordilleran magmatic arc in a crustal block that was probably originally connected to southern California about 80 to 100 million years ago. Hill and Dibblee (1953) were the first to postulate a total displacement of about 348 miles (560 km) for Mesozoic basement along the fault systems in coastal California.

Stop 4—Chimney Rock and the Historic Point Reyes Lifeboat Station Area

Stop highlights: Salinian granite, nonconformity, faults, marine wildlife viewing area

Before the railroad and modern highway system, shipping was the primary means of cargo and human transport.

Historically, the Point Reyes Peninsula was a primary hazard to coast navigation because of its close proximity to the port of San Francisco, because it juts out 10 miles (16 km) to sea, and because it is frequently enshrouded in fog. As a result of the untold loss of life and property from dozens of shipwrecks, a lifesaving station was built in the 1890s on the sheltered east side of Point Reyes. During its operation through the mid 20th century, observers walked the beaches on 4-hour shifts to watch for ships in trouble. With the development of modern maritime navigation systems and modern rescue craft, the Coast Guard ended the coastal watch in 1968. Still, several small fishing vessels and pleasure craft are lost practically every year in the treacherous waters around the point. Today, the historic Point Reyes Lifeboat Station is used for limited group overnight accommodations and other park activities.

The Chimney Rock Trail and the Sea Lion Overlook Trail both start at the parking area and both are worth investigating. **Be extremely cautious when approaching cliff areas. Active slumps are carving away at the ridgeline, undercutting the cliffs in some areas.**

The trail to Chimney Rock offers spectacular views of the Point Reyes headlands and of Drakes Bay. The trail to the Chimney Rock Overlook is about one mile. The overlook provides a view of a sea arch in addition to Chimney Rock, a large sea stack just offshore of the point. Both are formed in the Salinian granitic rocks (Porphyritic Granodiorite of Point Reyes of Clark and Brabb, 1997). Take the extra time to walk the loop trail along the south facing cliff top near the Chimney Rock Point. Another sea arch and many sea stacks are visible near the point and along the south facing shore of Point Reyes (figs. 9-18 and 9-19).

The nonconformable boundary between the granitic rocks and sedimentary rocks of late Miocene age are exposed in the sea cliffs along the Chimney Rock Trail and the trail that loops around the south side of the point (fig. 9-20). Green sandstone, rich in the mineral glauconite, is exposed locally along this unconformable surface. The sandstone unit is mapped as Santa Margarita Sandstone (Clark and Brabb, 1997), but the unit is probably younger than sandstone with the same name on the opposite side of Drakes Bay where the Santa Margarita Sandstone is overlain by a thick sequence of Santa Cruz Mudstone.

Figure 9-18. The cliffs and sea stacks at the east end of the Point Reyes headlands consist of granitic rocks. Chimney Rock (upper right) is a prominent sea stack. Note the sea arch formed in the fractured granitic rocks in the foreground.

Figure 9-19. This view is looking west along the south face of the granite headlands of Point Reyes. The image was taken from the loop trail on Chimney Rock Point. Drakes Bay is to the right.

Figure 9-20. Late Miocene sedimentary rocks rest nonconformably on granitic rocks and Point Reyes Conglomerate at Chimney Rock Point. The nonconformity is visible near the center of the image. The late Miocene rocks consist of a thin, intermittent basal bed of greenish glauconitic sandstone overlain by fine-grained siltstone and shale of the Purisima Formation. This view is looking toward the northwest from Chimney Rock. Drakes Bay in the distant right is on the opposite side of the point.

In the Point Reyes headlands area, this basal sandstone is directly overlain by sandstone, shale, and mudstone of the Purisima Formation of latest Miocene and Pliocene age (Clark and Brabb, 1997). Round sandy limestone concretions are weathering out of the Purisima Formation. **Please note that these outcrops are far too dangerous to investigate in the sea cliffs!**

The mesa-like top of Chimney Rock Point is capped by a marine terrace. Granitic cobbles from the Point Reyes Conglomerate are reworked into the marine terrace deposits. The terrace gravel is locally overlain by sand with a thin organic-rich soil horizon on top (fig. 9-21). The Point Reyes Conglomerate is well exposed and is accessible in the western end of the headlands near the Point Reyes Lighthouse area (see Stop 3). The conglomerate in the nearby headlands was probably the source of the conglomeratic material in the marine terrace deposits at Chimney Rock.

During low tide, the granitic rocks are well exposed along the beach near the lifeboat station, providing the dual opportunity to examine the rock and the marine wildlife that utilize the hard rock substrate. A short trail to Elephant Seal Overlook starts at the Chimney Rock parking area. Elephant seals, harbor seals, and other marine mammals frequently cover the cobble beach located at the intersection of Drakes Beach and the Chimney Rock (fig. 9-22). Although the beach is closed to public access, the overlook provides a relatively good view of the unconformable boundary between the Cretaceous granite and steeply eastward dipping strata of late Miocene age (Santa Margarita Sandstone and Purisima Formation). The Paleocene conglomerate exposed at the Point Reyes Lighthouse is not present along the Drakes Bay side of the promontory. The strata exposed in the sea cliffs in the east end of Drakes Bay reveal a syncline and an adjacent anticline; these folds are shown on the geologic map (see fig. 9-2).

Figure 9-21. Quaternary marine terrace deposits rest unconformably on late Miocene Purisima Formation. Rounded cobbles of granite and porphyry derived from the Point Reyes Conglomerate make up the base of the marine terrace deposit. The upper part of the terrace deposit consists of sand and a thin organic-rich soil horizon.

Stop 5—Drakes Beach (Kenneth C. Patrick Visitor Center)

Stop highlights: Purisima Formation, faults, fractures, porcellanite, synclines and anticlines

Drakes Beach is accessible from a 1.5-mile (2.4 km) drive along an access road that intersects Sir Francis Drake Boulevard at 16.2 miles (26 km) from Highway 1, and 5.8 miles (9 km) north of the end of the boulevard at Point Reyes Lighthouse. The Kenneth C. Patrick Visitor Center is located at the beach parking area. Drakes Beach is a popular destination on warm weekends in the late summer.

Notes from the journals of the Sir Francis Drake voyage (1577 to 1580) suggested the white cliffs of what may now be Drakes Bay were very similar in appearance to England's White Cliffs of Dover. The cliffs of Drakes Bay are also reminiscent of those on the Channel Islands. The rocks exposed in the cliffs consist of porcellanite and glauconitic mudstone, siltstone, and sandstone and bear fossils of late Miocene to Pliocene age (Clark and Brabb, 1997; fig. 9-23). The porcellaneous character of the rock comes from original sediment that was rich in siliceous skeletal material of marine plankton. Glauconite is a greenish hydrous-potassium-iron silicate mineral common in marine sedimentary rocks that often is associated with fossilized invertebrate fecal material. The sedimentary rocks formed from sediments that were deposited under the sea while the landmass (that is now the Point Reyes Peninsula) was submerged offshore

Figure 9-22. This beach gravel bar is commonly covered with resting sea lions. The view is to the north from the end of the trail at Elephant Seal Overlook near the historic Point Reyes Lifeboat Station. The beach cobbles consist of granitic rock eroded from exposures along the shore near the lifeboat station and extending to the eastern point at Chimney Rock. In the distance, the steeply dipping sedimentary layers consist of late Miocene marine sedimentary rocks (Santa Margarita Sandstone and lower Purisima Formation). The dipping strata are along the western flank of a syncline exposed in the sea cliffs at the west end of Drakes Beach.

during its plate-tectonic voyage northward along the California coast. Galloway (1977) originally named the geologic units exposed in the sea cliffs the Drakes Bay Formation. However, Clark and others (1984) renamed the units the Purisima Formation to match the equivalent units that occur along the coast in Santa Cruz and along the San Francisco Peninsula.

A walk along the beach provides an opportunity to examine the marine beds, their orientation, as well as small faults, fractures, and joints in the rock exposed in the sea cliffs and on the remnants of a low, wave-cut bench located a short walk east of the Visitor Center (fig. 9-23). Viewed on a larger scale, the overall geologic structure of the Point Reyes Peninsula is revealed by the orientation of the layered sedimentary rocks exposed in the sea cliffs along the shore of Drakes Bay. The rock layers near the mouth of Drakes Estero at the east end of Drakes Beach form the center point of a broad, gentle syncline between the structural highs of Inverness Ridge and the Point Reyes headlands. The structural axis of the Drakes Bay syncline runs to the northwest along the west shore of Drakes Estero and roughly parallels the structural trend of Inverness Ridge and the San Andreas Fault Zone.

While standing on the beach you can see why the National Park Service encourages you to stay away from the base of the cliffs. Parts of the cliff are constantly giving way, showering the area below with falling rock and debris. The cones of debris that build up along the base of the sea cliffs between storms and high tides show how quickly the landscape is changing along the coast.

Stop 6—Tomales Bay State Park

Stop highlights: Salinian granitic rocks, Tomales Bay, mixed evergreen forest, Bishop pines

Tomales Bay State Park is a good destination to study the geology and ecology of the west shore of the bay. The park entrance is located along Pierce Point Road about 1.2 miles (2 km) north of the intersection with Sir Francis Drake Boulevard. Although the park requires a day-use fee per vehicle, it is worth a visit, especially to take advantage of the park's picnic area or a walk or even a swim at one of the several sheltered sandy beaches along the shore of Tomales Bay. The park is perhaps best known for its Bishop pine forest. Bishop pine (*Pinus muricata*) occurs only as discontinuous relict stands along the California coast, occupying north-facing slopes where it can maximize fog exposure and precipitation. Bishop pines inhabit areas with shallow, acidic and poorly drained soils associated with the weathering of granitic- and shale-parent material.

Cliffs of granitic composition crop out along the shore of Tomales Bay (fig. 9-28). The plutonic rocks of Inverness Ridge and Tomales Point are best described as granitic in composition. They range in composition from granodiorite, quartz diorite, to granite in composition, and contain some pegmatite and aplite intrusions (see more discussion about granitic rocks in Stop 7 and 8).

Stop 7—Kehoe Beach

Stop highlights: Salinian granitic rocks, aplite dikes, Laird Sandstone, Monterey Formation, nonconformity, faults, avalanche and debris chutes, sea cliffs

Kehoe Beach provides access to a variety of geologic features in a scenic setting. A half-mile trail starts at a parking area on Pierce Point Road and follows a freshwater marsh to the beach. Cliffs of steeply dipping layers of Monterey Forma-

Figure 9-23. These sea cliffs and wave-cut bench are along Drakes Beach near the Kenneth C. Patrick Visitor Center. Light gray siliceous mudstone in the sea cliffs is of the Drakes Bay Formation (Galloway, 1977) or equivalent Purisima Formation (Clark and Brabb, 1997). Fossils indicate the sedimentary rocks are of late Miocene age.

Figure 9-24. This view looking south from along Pierce Point Road shows the high ridgeline of Inverness Ridge at Mount Vision. The low hilly escarpment on the right consists of Monterey Formation. The Laird Sandstone underlies the grassy pastures in the foreground. This view is about a mile south of the entrance to Tomales Bay State Park.

Road Log for Pierce Point Road (Optional Route)

Route highlights: Abbots Lagoon, Kehoe Beach, McClures Beach, Tomales Point, granitic rocks, schist, Laird Sandstone, Monterey Formation, ancient dune deposits, headlands, coastal prairie, Tule elk

A trip to the north end of the Point Reyes Peninsula along Pierce Point Road provides opportunities to see many unique geologic and ecological features. Pierce Point winds northward for 7.5 miles (12 km) across the coastal prairie. Along the way, the road passes Tomales Bay State Park, several active dairy farms, Abbotts Lagoon, and Kehoe Beach before entering the Tule Elk Reserve. The road ends at historic Pierce Point Ranch near McClures Beach. Outcrops of Laird Sandstone can be seen along the Pierce Point Road (between Tomales Bay State Park and Kehoe Beach). Elk herds grazing across the coastal prairie are a scene not to be missed! Early visitors to the Point Reyes Peninsula described great herds of elk. However, the original elk population on the peninsula was wiped out by over hunting and competition with cattle ranching by the 1870s. The elk were reintroduced to the area in 1978.

With extra time, it is worth considering a hike to one of the beaches (Kehoe Beach or McClures Beach), or the long hike to Tomales Point itself. **Please note that riptides and pounding surf can be extremely dangerous along the Pacific beaches; do not attempt to walk along the sea cliffs during high tide or during inclement weather. Poison oak is common along trails and in the back beach areas.**

Distance	Description
0.0 mi (0.0 km)	Intersection of Pierce Point Road with Sir Francis Drake Boulevard. The intersection is located on a pass through Inverness Ridge. Bishop pine and Douglas fir forest dominate the landscape in the area.
1.2 mi (1.9 km)	Entrance to Tomales Bay State Park on right (see description for **Stop 6—Tomales Bay State Park**). Continuing north along Pierce Point Road for the next 2 miles, the road crosses cattle and dairy ranch lands. Laird Sandstone and some Monterey Formation underlie this section of the route; changes in lithology are reflected by vegetation contrasts. An escarpment of low hills to the left (south) of the road consists of more resistant beds of the upper Monterey Formation capped unconformably by the softer Santa Margarita Sandstone (fig. 9-24).
3.5 mi (5.6 km)	Abbotts Lagoon is on the left (west). Coastal dunes and beach form the barrier across the entrance of this submerged valley (fig. 9-25). A hilly escarpment of Monterey Formation capped by Santa Margarita Sandstone runs along the left (south) side of the lagoon and valley.
5.6 mi (9.0 km)	Kehoe Beach parking is on both sides of the road (see description for **Stop 7—Kehoe Beach**). Laird Sandstone is exposed in the hillside south of the trailhead to Kehoe Beach. A mile to the north, the road passes Kehoe Ranch and ascends to the top of a ridge underlain by granitic rocks. Much of the Point Reyes Peninsula is visible to the north from the top of the ridge about 2 miles south of Kehoe Beach.
7.9 mi (12.7 km)	Boundary of the Tule Elk Reserve (fig. 9-26).
9.2 mi (14.8 km)	Upper Pierce Point Ranch at end of Pierce Point Road. McClures Beach access is to the left (west). A trail to Tomales Point starts at historic Pierce Point Ranch (fig. 9-27). The hike to Tomales Point is about 8 miles (out and back). Exceptional views of the granite headlands on the Pacific side can be seen along the trail. Some sections of the trail cross loose dune sand, particularly near the point. The hike is not recommended in cold and

Continued.

	windy weather. However, on a warm early spring day, hikers will enjoy the wildflowers and may be treated with glimpses of pods of whales migrating around the point between the Pacific shore and Tomales Bay.
9.6 mi (15.4 km)	McClures Beach parking area (see description for **Stop 8—McClures Beach**).

Figure 9-25. Abbotts Lagoon as seen from the parking area on Pierce Point Road. The hill to the left of the lagoon consists of Monterey Formation capped by Santa Margarita Sandstone. Coastal dunes make up the hills to the right of the lagoon.

Figure 9-27. View looking north toward Tomales Point. Tomales Bay is to the right; the Pacific Ocean is to the left. Historic Pierce Point Ranch is in the center of the image. This image was taken from a ridgeline near the south end of the Tule Elk Reserve along Pierce Point Road.

tion are exposed where the trail intersects the beach (fig. 9-29). Monterey Formation underlies the pasture lands and coastal dunes extending southward to Abbotts Lagoon.

Farther north along the beach, cliffs of Laird Sandstone give way to Salinian granitic rocks (figs. 9-30 to 9-32). The nonconformity between the massive Laird Sandstone (middle Miocene) and the underlying Salinian granitic basement is well exposed in sea cliffs at the north end of the beach (fig. 9-31). The sea stacks of granite covered with mussels stand

Figure 9-26. Tule elk along Pierce Point Road.

Figure 9-28. Cliffs of Salinian granitic rocks (tonalite) crop out along the shore in Tomales Bay State Park. The cliffs and slopes along the west side of Inverness Ridge are covered with a unique mixed evergreen forest. Red alder dominates the forest community near the shore, whereas Douglas fir and Bishop pines dominate higher on the ridge.

Figure 9-29. Steeply northward dipping beds of Monterey Formation are exposed in the sea cliff next to where the Kehoe Beach access trail reaches the beach. The rock consists of thinly laminated siliceous mudstone and siltstone (porcellanite).

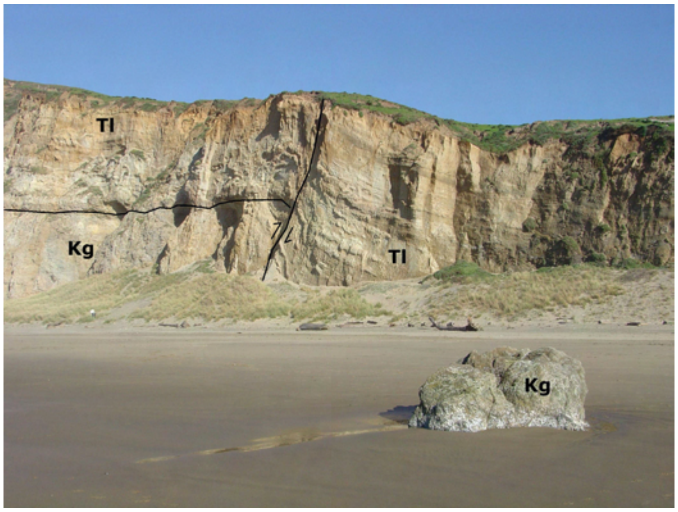


Figure 9-31. At Kehoe Beach, the Laird Sandstone (Tl) rests nonconformably on Cretaceous granitic rocks (Kg). The sandstone is offset by a high angle reverse fault.

out along the beach. A well exposed high-angle reverse fault is exposed in the cliff. The massive beds of the Laird Sandstone are offset by about 130 feet (40 m) along the main fracture of the exposed fault (fig. 9-31). The fault trace creates an escarpment in the pastures above the sea cliff (see fig. 9-30).

Fossil marine mollusks and echinoids found at the base of the Laird Sandstone on Kehoe Beach indicate that deposition occurred in shallow during middle Miocene time (Clark and Brabb, 1997). These sandy facies grade into finer grained rocks (sandstone, siltstone, and shale) of the lower Monterey Formation. The Monterey Formation grades upward into siliceous shales, porcellanite, and chert. The upper Monterey Formation yields fossil benthic foraminifera that suggest the sediments were deposited in bathyal depths of about 600 to 13,000 feet (200 to 4,000 m) during middle to late Miocene time (Clark and others, 1984).

The granitic rocks exposed at Kehoe Beach are a complex mix of lithologies (fig. 9-32). Intrusive igneous rocks consist of granite, granodiorite, quartz diorite, and tonalite, and include dikes of aplite and alaskite—a classification of

Figure 9-30. This view is looking north along the sea cliffs at Kehoe Beach. Gently dipping layers of Laird Sandstone are exposed in the lower sea cliffs in the foreground, whereas the higher cliffs in the distance are granitic rocks.

Figure 9-32. The granitic basement rocks at Kehoe Beach consist of a mix of granodiorite with inclusions of older metamorphic rock that are cut by dikes of aplite and alaskite. Aplite is a light-colored, fine-grained rock with granitic texture, consisting essentially of quartz and orthoclase. Alaskite is also a light-colored granitic rock that has orthoclase, microcline, and subordinate quartz (see fig. 9-33). Both rock types lack mafic constituents.

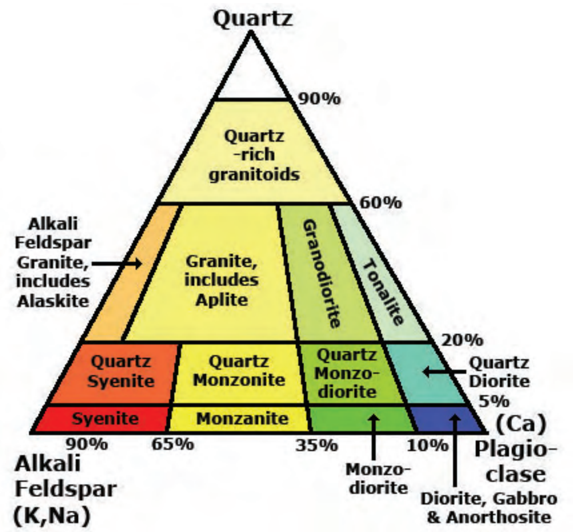


Figure 9-33. Classification of granitic rocks based on composition of feldspars (K-, Na-, and Ca-rich varieties) and quartz. Mafic components (igneous minerals rich in iron and magnesium) are not included in this classification. This classification of granitic rocks is modified from an igneous petrology chart prepared by the International Union of Geological Sciences and presented by Best (1982).

Figure 9-35. View looking toward the north end of McClures Beach where the granitic basement has a different appearance than at the opposite end of the beach. Clark and Brabb (1997) assigned the name “Tonalite of Tomales Point” to rocks exposed on the peninsula north of McClures Beach.

these rocks is illustrated in fig. 9-33. Some bodies of darker schist and gneiss included in the granite probably represent fragments of more ancient metamorphic rock (xenoliths) that predate the intrusive igneous rocks. These granitic rocks are probably mid-Cretaceous in age (roughly 80 to 100 million years old) and the metamorphic rocks are much older, with zircon-based radiometric ages ranging from Paleozoic to Precambrian age (Ross, 1983). Clark and Brabb (1997) include the granitic rocks exposed at Kehoe Beach within a mapped unit called “Granite and Granodiorite of Inverness Ridge.”

Figure 9-34. View looking toward the south end of McClures Beach. The beach is located in a cove along the Pacific side of Tomales Point. The Salinian granitic basement exposed at the south end of the beach is lithologically different than the rock exposed at the north end of the beach. Clark and Brabb (1997) include the lithologies exposed at the south end of the beach within a map unit they named “Granodiorite and Granite of Inverness Ridge.”

The granitic rock exposed along Kehoe Beach is heavily fractured and displays evidence of faulting, both ancient and more recent. The highly fractured character of the rocks makes them dangerous to climb. Debris chutes formed in the granitic rocks channel falling material onto talus cones along the shore; these are eroded away during high wave activity. Some of the chutes start from cave-like overhangs beneath the base of the Laird Sandstone (fig. 9-31).

Stop 8—McClures Beach

Stop highlights: Salinian granitic basement rocks, granodiorite, tonalite, eolianite

The Salinian granitic basement rocks are well exposed at McClures Beach (figs. 9-34 and 9-35). A half-mile trail leads from a parking area downhill to the beach located in a cove between massive headlands on the Pacific side of the Tomales Point peninsula. The headlands at the south end of McClures Beach mark a lithologic boundary in the Salinian basement. The exposures of the “Granite and Granodiorite of Inverness Ridge” exposed at Kehoe Beach give way to the “Tonalite of Tomales Point” (Clark and Brabb, 1997). The Granodiorite and Granite of Inverness Ridge is of middle Cretaceous age and contains inclusions (xenoliths) of older metamorphic rock that have cross cutting dikes of aplite and alaskite (see figs. 9-32 and 9-33). The Tonalite of Tomales Point on northern McClures Beach to Tomales Point has a more uniform texture and appearance (fig. 9-35). Tonalite is a rock rich in plagioclase, quartz, and hornblende or biotite, but has slightly less orthoclase than granodiorite. Clark and Brabb (1997) note the similarity to the rock at Tomales Point with similar rock exposed on Bodega Head (located about 10 miles (16 km) north of Tomales Point) and present a recalculated radiometric age of 94.3 million years (early Late Cretaceous) for the tonalite.

A nonconformity between the granite and overlying ancient dune deposits (eolianite) of Quaternary age can be seen near where the trail intersects the beach (fig. 9-36). The ancient dune sands probably accumulated in an earlier valley in the Quaternary Period before or during the last ice age (Wisconsin) and before the modern rise in sea-level that is responsible for the ongoing coastal erosion. The sandstone is fairly tightly cemented, but preserves bedding structures consistent with features of wind-blown sand deposits. The sandstone fills an ancient stream valley that is being exhumed by modern McClures Creek.

Stop 9—Mount Vision on Inverness Ridge (Optional Route)

Stop highlights: Granitic rocks, area of the 1995 Vision Fire, views of Tomales Bay and Drakes Estero (drowned river valleys)

Mount Vision Road winds uphill for about 4 miles (7 km) along the crest of Inverness Ridge. Inverness Ridge is a long and narrow mountain with a core of Salinian crystalline basement rocks. These rocks consist of Cretaceous granitic intrusive rock with some older metamorphic rocks. The older rocks are commonly referred to as "roof pendants"—they are pieces of the original rock that did not melt when large igneous bodies formed the southern Sierra Batholith in Cretaceous time. The Salinian crystalline basement rocks are bounded by the San Andreas Fault Zone to the east and are blanketed by gently dipping sedimentary rocks of late Tertiary age on the south and west. Unfortunately, no significant bedrock exposures are accessible along the Mount Vision Road except occasional granitic boulders placed around parking areas. More accessible exposures of Salinian granitic rocks are available at Stops 6 and 7.

On a clear day, the drive along Mount Vision Road provides sweeping views of the Point Reyes Peninsula, Tomales Bay, and upland regions in Marin and Sonoma Counties to the east (fig. 9-37). Parking areas near the top of Mount Vision also provide a view of Drakes Estero (fig. 9-38). "Estero" means estuary or marsh in Spanish. Tomales Bay and Drakes Estero are both stream valleys that were flooded by the roughly 400 foot (120 m) rise in sea level since the end of the last glacial maximum of the Quaternary Period, about 18,000 years ago. The bays are flushed by marine currents and tides. Compared with Tomales Bay, Drakes Estero receives only a small quantity of freshwater input from streams and springs.

Much of the Mount Vision area, about 5,000 hectare (12,354 acres) of maritime scrublands, Bishop pine forest, and grasslands, burned in a 1995 fire (called the Vision Fire) that extended from Limantour Beach to much of the crest of Inverness Ridge. At least 50 years of past fire suppression activities prior to the fire contributed to the buildup of combustible material, leading to the uncontrollable firestorm that engulfed much of the central Point Reyes Peninsula region.

Figure 9-36. Quaternary dune deposits exposed by coastal erosion crop out near the McClures Beach access trail. These old dune deposits are well cemented and appear to be filling an old valley that existed in close proximity to the modern stream valley along the beach access trail.

Figure 9-37. This view from the summit of Mount Vision on Inverness Ridge is looking northeast toward Tomales Bay. Bolinas Ridge (in the distance) runs along the east side of the San Andreas Rift Valley on the far side of the bay. Note the vegetation contrast of the mixed evergreen forest on the Point Reyes side of the bay compared to the grasslands that dominant the landscape on the east side of the bay.

Although most of the fire was on park land, at least 45 homes were destroyed in nearby Inverness Park. The fire had devastating effects on some plant and animal species, whereas other species, both native and exotic, benefited from the new space available after the fire. For example, the Point Reyes mountain beaver population was partially devastated by the fire and loss of habitat. On the other hand, Bishop Pines release their seeds from resinous cones during a fire, a natural way of propagation for the species. The long-term regrowth of plant and animal communities are being monitored by the National Park Service (National Park Service, 1996; Brown and Holzman, 1998).

Stop 10—Limantour Road (Optional Route)

Stop highlights: Estuary, lagoon, sand spit, marine terraces

Limantour Road intersects Bear Valley Road about 1.4 miles (2.2 km) west of the Park Headquarters. Driving west, Limantour Road crosses Inverness Ridge before descending to Limantour Beach. The highest point on Point Reyes Peninsula is Mount Wittenberg, elevation 1,407 feet (429 m). The summit is located about a mile south of the Sky Trail parking area near the high point along Limantour Road about 3 miles (5 km) west of Bear Valley Road. Older metamorphic rocks (marble, schist, gneiss, quartzite, and aplite dikes) are present in the upland region along Inverness Ridge between Mount Wittenberg and Mount Vision. These rocks predate the Cretaceous granitic rocks and are roof pendants in the greater intrusive complex of the Salinian basement (see description of the granitic crystalline basement for Stop 9). Unfortunately, because of intense weathering in the upland area, none of these rocks are exposed along the road. The upland area receives about 40 inches (102 cm) of precipitation per year, mostly as plant initiated condensation associated with fog.

The Point Reyes Hostel and Clem Miller Environmental Education Center are located 5 miles (8 km) west of the intersection with Bear Valley Road. Both are an optional destination for overnight group housing, but planning is needed well in advance. Parking access to Limantour Beach and Lagoon (Estero de Limantour) is located another 1.5 west (2.4 km) of the Environmental Education Center.

Sedimentary formations of middle to late Miocene age crop out in the hillsides west of granitic rocks that make up Inverness Ridge. The sedimentary rocks dip steeply to the west (about 30 degrees). Laird Sandstone and Monterey Formation are poorly exposed in the upland region east of the Environmental Education Center. The Santa Margarita Sandstone of Clark and Brabb (1997) crops out along a faint northwest-trending escarpment in the vicinity of the Environmental Education Center. The Coast Trail starts at the Point Reyes Hostel and follows a canyon west for about 1.5 miles (2.4 km) to the beach. The canyon cuts downhill through increasingly younger beds of the Purisima Formation.

Limantour Beach is on a spit built by longshore currents that flow northward along the beach (fig. 9-39). The current is generated by the refraction of prevailing wave swells as they arrive from the northern Pacific region. As the prevailing waves are refracted around the point, they come onshore along the beaches in Drakes Bay and Limontour beach from a more southerly direction. Over time, this refraction of wave energy helped erode the crescent-shaped coast, and is responsible creating the northward-flowing longshore current that helped build up the barrier island (or spit) at Limontour Beach. Similar processes helped create the barrier island spit at the Bolinas and Stinson Beach area (Stop 13). The lagoon behind the bar-

Figure 9-38. This view from the summit of Mount Vision is looking southwest toward Drakes Estero. The headlands of Point Reyes are in the distance.

Figure 9-39. Estero de Limantour is a small bay and lagoon on the south end of Drakes Bay. The high headland area of Point Reyes is in the distance. Note the crescent shape of Drakes Bay. The barrier island associated with Limontour Beach is actually a spit that built up from sediment that migrated northward along the coast, transported by prevailing longshore currents.

rier (Limantour Estero) is a popular destination for bird watching, particularly during migration periods.

Blackened, charred stumps along the road are a reminder of the extensive 1995 Vision Fire that burned throughout the central Point Reyes Peninsula region, extending from Limantour Beach eastward across Inverness Ridge. In most areas, shrub and underbrush have returned to near pre-fire conditions, but it will take perhaps another century to restore the Douglas fir and Bishop pine groves that thrived along the upland areas before the fire.

Stop 11—Olema Valley (rolling stop)

Stop highlights: San Andreas Fault Zone, linear rift valley, shutter ridges, deflected streams, Calera Limestone

Most of Olema Valley is now part of National Park Service holdings and is protected from future development, and for good reason. Three major fault systems converge in Olema Valley (see fig. 9-2). The most catastrophic surface rupture during the 1906 earthquake happened in the Olema Valley region (fig. 9-40). Fortunately, the area was sparsely populated at the time of the great earthquake.

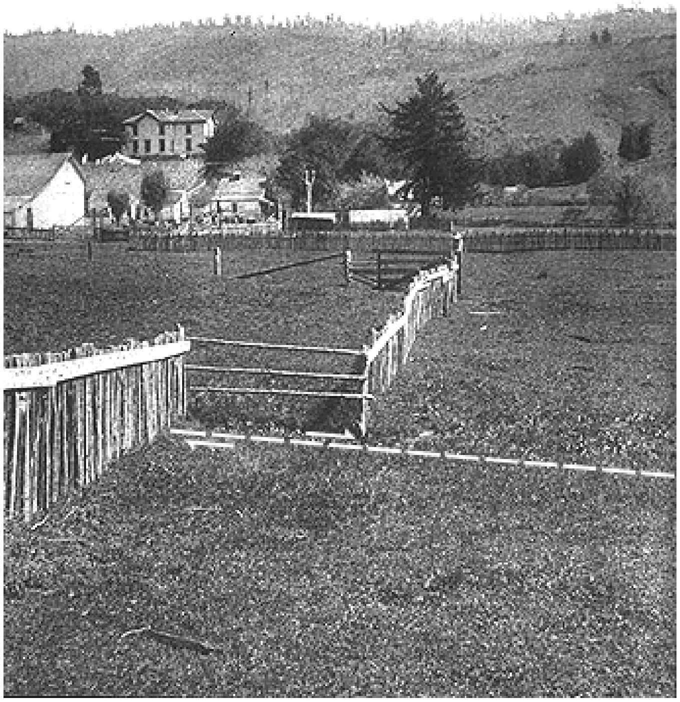


Figure 9-40. This historical photograph of an offset fence near Bolinas, California was taken by G.K. Gilbert shortly after the 1906 earthquake (Gilbert, 1908). The offset fence shows a right-lateral slip of about 8.5 feet (2.6 m). Also note the high degree of deforestation shown on the distant hillsides in this photograph.

The thick second growth forest of oak, mixed evergreens, and redwood in Olema Valley masks many of the geologic features of the rift valley. None of the surface rupture features described by Gilbert (1907) after the great 1906 earthquake remain visible today. However, along Highway 1 between Olema and Bolinas Lagoon, it is possible to see low, linear ridges (fault scarps) and depressions that flood during wet periods (sag ponds) and reveal the presence of great faults that run through the valley.

Olema Valley can be seen in two ways–by vehicle or by foot. Unfortunately, by vehicle there are few pull off where it is possible to stop to look at the San Andreas Fault Zone and associated landscape features. Shutter ridges and escarpments can be glimpsed while driving along the road. If hiking is an option, the Rift Zone Trail extends southward from the Bear Valley Visitor Center parking area to another parking area at Five Brooks–a distance of about 5 miles (8 km). Combined with the Earthquake Trail at the visitor center, the trail crosses or parallels the San Andreas Fault in many places or climbs or crosses shutter ridges and escarpments associated with the fault zone. South of Five Brooks, the Olema Valley Trail continues southward about 4 miles (7 km) along the rift valley to intersect with Highway 1 near Bolinas. Be sure to get trail conditions before attempting this hike especially after wet weather (see the park trail map on http://www.nps.gov/pore/).

An unusual stream drainage pattern in Olema Valley reveals the past motion of the faults in the valley. Many of the small streams draining from the uplands on both sides of the valley display right-lateral offset where they cross faults in the valley. For about a 2 mile (3 km) section of the valley midway between Five Brooks and Bolinas Lagoon two streams flowing in opposite directions drain from the valley. Pine Gulch Creek on the west side of the valley drains into Bolinas Lagoon, whereas Olema Creek on the east side of the valley drains northward into Tomales Bay. A low shutter ridge along the 1906 trace of the San Andreas Fault divides the two drainages where they run parallel to each other. On a larger scale, as the Point Reyes Peninsula gradually migrated northward, Inverness Ridge, itself a great shutter ridge, deflected all the stream drainages northward into the linear rift valley drained by Olema Creek and its submerged extension beneath Tomales Bay. In map view, Lagunitas and Nicasio creeks are deflected streams that were diverted northward into Olema Valley.

Part of the geologic story of Olema Valley is a small outcrop area of Calera Limestone located about a mile south of Five Brooks in central Olema Valley. An unsuccessful venture to utilize the limestone began with the construction of the Olema Lime Kilns in 1850. However, the low quality of the limestone, limited supply, and a poor economy forced the abandonment of the kilns by 1855; only ruins remain today. The presence of Calera Limestone reveals an important clue about the geologic development of the San Andreas Fault Zone in Olema Valley. Calera Limestone also occurs in the Permanente Terrane of the Franciscan Complex in the Santa Cruz Mountains and on the San Mateo Coast near Pacifica. Rocks of the Permanente Terrane occur only in a narrow belt of rock within the rift zone between the “eastern” and “western” boundary faults of Galloway, (1977). The mid Cretaceous-age limestone-bearing terrane between the boundary faults does not correlate with the Franciscan sandstone, basalt, and greenstone on the east side of the fault zone on Bolinas Ridge, nor does it correlate with the granitic basement and Tertiary-age marine rocks of Inverness Ridge to the west. The enigmatic limestone is part of a thin sliver of Franciscan basement rock that is bounded by faults within the rift associated with the fault system.

Stop 12—Palomarin Beach

Stop highlights: Duxbury Reef, Palomarin slump, offset marine terrace deposits, syncline, Santa Cruz Mudstone

The Palomarin Beach area is a good place to observe a variety of geologic processes and to observe seashore wildlife. The parking area for Palomarin Beach is located at the end of Mesa Road two miles west of the intersection of Olema-Bolinas Road in the town of Bolinas. The Point Reyes Bird Observatory (field station) is also situated along Mesa Road about a half mile from the end of the road. **It is important to plan to arrive at low tide, otherwise access to the beach and tide-pool area is potentially dangerous if not impossible. Hikers along the coast have been trapped along the sea cliffs by the rising tide. In addition, be aware that loose material is constantly sloughing off the sea cliffs.**

The Santa Cruz Mudstone is the surficial bedrock throughout the southern Point Reyes Peninsula and is largely responsible for many of the topographic characteristics of the area. The Santa Cruz Mudstone is exposed in the sea cliffs along the coast at Palomarin Beach and southward to the end of the peninsula at Duxbury Point. Clark and Brabb (1997) reported that the Santa Cruz Mudstone is about 6,600 feet (2000 m) thick at the southern end of the peninsula at Bolinas Mesa but pinches out to the east of Drakes Bay. The Santa Cruz Mudstone contains fossil microplankton (diatoms and benthic foraminifera) that indicate the sedimentary rocks are of late Miocene age. This thick section of siliceous mudrock is complexly folded and faulted, but mostly dips quite steeply to the west of the structural high at the south end of Inverness Ridge. The layers of Santa Cruz Mudstone dip westward in the range of 20 to 60 degrees. The eastern extent of the Santa Cruz Mudstone borders the San Gregorio Fault (or “west boundary fault” of the San Andreas Fault Zone of Galloway (1977). It is bounded on the east by offset older Quaternary marine sediments of the Merced Formation and younger marine terrace deposits that are preserved in the rift valley area near Bolinas. From viewpoints along the coast, a well developed marine terrace is visible along the southern peninsula, with marine terrace deposits resting on an angular unconformity above the dipping layers of mudstone.

The steep shoreward dip is responsible for a large landslide complex along the shore north of Palomarin Beach. The landslide offsets bedrock of Santa Cruz Mudstone and marine terrace deposits (figs. 9-41 and 9-42, and see the landslide area shown on fig. 9-2). Beach erosion is constantly undercutting the toe of the slide area which initiates farther slide motion. The highly brittle character of the siliceous mudstone makes it prone to fracturing and subsequent erosion. The pounding action of waves has cut an extensive wave-cut platform that locally extends seaward for nearly a half mile. At low tide, a syncline is well exposed in the Santa Cruz Mudstone at the toe of the Palomarin slide (fig. 9-41). The wave-cut platform extends both northward and southward along the coast.

Stop 13—Duxbury Reef

Stop highlights: Santa Cruz Mudstone, steeply dipping strata, views of the Gulf of the Farallones

The southern tip of Point Reyes Peninsula is called Duxbury Reef and is considered the largest shale reef in North America. Like the Point Reyes Headlands and Drakes Bay to the north, Duxbury Reef has been the site of many shipwrecks; materials reportedly lost on the reef include food, merchandize, animals, hides, wood, coal, petroleum products, mail, an organ, whiskey, and gold (National Oceanic and Atmospheric Administration, 2005). The reef was named after the shipwreck of the Duxbury that occurred there in 1849. In 1878, a freighter named the Western Shore bearing a heavy load of Alaskan coal was driven by ashore by a combination of strong northerly currents and possibly pilot error. It was reported that coal from the shipwreck washed up on Point Reyes beaches for decades after the ship-

Figure 9-41. A large slump is an impressive landscape feature at Palomarin Beach. At low tide a plunging anticline is exposed in a wave-cut platform below the toe of the great slump. Dipping marine-terrace deposits unconformably overlie marine mudrocks of the late Miocene-age Santa Cruz Mudstone. These marine terrace deposits are offset by rotation of the large slump block. The terrace deposits are best observed from the beach (see fig. 9-42). The Point Reyes headlands are in the distance.

wreck (Hobson, 1994). Extensive tide pools lined with seaweed, beds of mussels, and teaming with a variety of invertebrates are exposed at low tide. A trail to the tide pools at Duxbury Reef starts at Agate Beach County Park. From Bolinas, take Mesa Road about 0.7 miles (1.1 km) west, take Overlook Drive 0.5 miles (0.8 km) south, and then Elm Road 0.7 miles (1.1 km) west to the Agate Beach parking lot at the end of the road.

The Santa Cruz Mudstone is well exposed in the sea cliffs and in the exposed reef at low tide. More resistant layers within the steeply dipping strata produce ridges that extend seaward, whereas softer layers and fractures which eroded more quickly form parallel tidal channels (fig. 9-43). The broad shale reef created by coastal erosion of the Santa Cruz Mudstone extends seaward for nearly a half mile into outer Bolinas Bay. The reef is part of the Gulf of the Farallones Marine Sanctuary (for more information about the Gulf of the Farallones, see Karl and others, 2000).

Stop 14—Bolinas and Stinson Beach Area

Stop highlights: Drowned river valley, Franciscan Complex, San Andreas Fault Zone

The Gold Rush of 1849 initiated one of the greatest migrations in human history. Wood for building and firewood was needed to satisfy the growing population in San Francisco. Bolinas Lagoon served as a port for small flat bottom boats to ferry wood and lumber derived from the redwood forests in Olema Valley. A historic photograph taken by G.K. Gilbert after the 1906 earthquake shows that the hillsides were largely stripped of their redwood and Douglas fir forests by that time (see fig. 9-40). Discovery of a copper vein near the head of Bolinas Lagoon initiated marginally economic mining efforts that started in 1863 and continued intermittently until 1918. The development of the North Coast Railroad in the mid 1870s diverted much of the commercial activity associated with logging and ranching away from the Bolinas area, but fishing, tourism, and residential development continued. The Mount Tamalpais 15 minute quadrangle map of 1897 shows several dozen established buildings on the north side of the harbor entrance to Bolinas Lagoon, but the barrier island was uninhabited. An overland route that would eventually become the Shoreline Highway (U.S. Highway 1) was already established in 1897. The beach community started in about 1900 with a tent colony in the beach dunes adjacent to the lagoon, and a subdivision along the shore was planned and developed by Nathan H. Stinston starting shortly after the 1906 earthquake (figs. 9-44).

Figure 9-42. View of the slump block at Palomarin Beach (also shown in fig. 9-41). This view shows the angular unconformity between northwest dipping Santa Cruz Mudstone and the overlying marine terrace deposits. The slump block has rotated the marine terrace deposits so that they dip toward the shore. A small stream cascades from a ravine carved at the base of the headwall escarpment of the slump.

Figure 9-43. Duxbury Reef extends southward about a half-mile from the southern end of the Point Reyes Peninsula, just west of Bolinas Lagoon. The reef and sea cliffs consist of steeply westward dipping beds of Santa Cruz Mudstone. This view is looking south toward the Gulf of the Farallones.

Three major earthquake faults of the San Andreas Fault Zone merge together from the south in the Bolinas area–the Golden Gate, San Andreas, and San Gregorio Faults, from east to west, respectively (figs. 9-45 and 9-46, and also see fig. 9-2). To the south, these faults are submerged or covered by sediments beneath the beach and lagoon. The three faults converge northward in the Olema Valley to the narrowest point of the fault zone near Five Brooks (where it is still about a half kilometer wide). The detailed geometry of how these faults merge or might behave during earthquakes is unclear.

The Golden Gate Fault (called the "east boundary fault trace" by Galloway, 1977) runs along the eastern shore of Bolinas Lagoon. Its location can be inferred from exposures in road cuts along Highway 1. Near the northern end of the lagoon poorly unsorted and poorly consolidated alluvial terrace gravels of Quaternary age (the Olema Formation) can be

Figure 9-44. These cracks along the shore of Bolinas Lagoon formed during the 1906 earthquake. Photograph by G. K. Gilbert (1908). This view is looking southeast along the western shore of the lagoon toward what was then the undeveloped barrier spit that is now home to Stinson Beach.

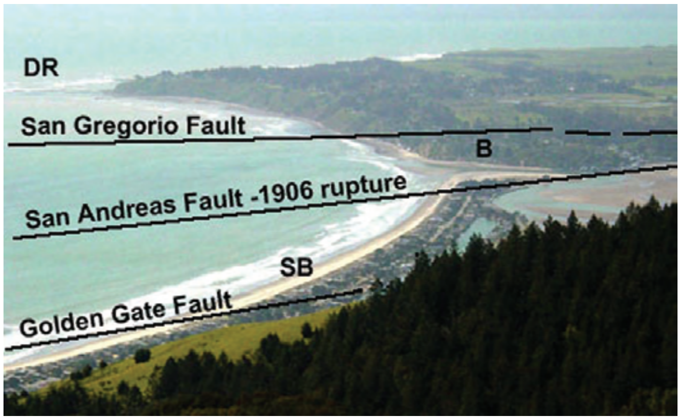


Figure 9-45. View is looking down toward Stinson Beach (SB) and Bolinas Bay from an overlook area on Bolinas Ridge along Bolinas-Fairfax Road. The town of Bolinas (B) is on the west side of the mouth of Bolinas Lagoon. Duxbury Reef (DR) is at the south end of the Point Reyes Peninsula. Lines show the approximate location of the three great faults—the San Gregorio Fault, San Andreas Fault (1906 rupture trace), and the Golden Gate Fault—that merge to form a single (or combined) fault zone in Olema Valley. How the faults interconnect, both near the surface and at depth, is uncertain. Onshore they collectively become part of the San Andreas Fault Zone and Olema Valley is a San Andreas Rift Valley.

Figure 9-46. View looking north from Highway 1 toward Stinson Beach and Bolinas Lagoon. The crest of Inverness Ridge is in the center of the image. Olema Valley, the rift valley of the San Andreas Fault Zone, is to the right (east) of the ridge. Bolinas Ridge is to the far right (east) of Olema Valley.

seen in the road cut. Clark and Brabb (1997) show that deposits of terrace gravels occur scattered throughout Olema Valley. Franciscan rocks occur along the eastern side of the Golden Gate Fault and are exposed extensively along Highway 1 and the coast southward toward the Marin Headlands (figs. 9-47 and 9-48).

The geologic maps of both Galloway (1977) and Clark and Brabb (1997) show that the main trace of the San Andreas

Figure 9-47. Older Quaternary alluvial gravels of the Olema Formation overlie weathered Franciscan bedrock along Highway 1 south of the intersection of Bolinas-Olema Road along Bolinas Lagoon. The age of the gravels is about 55,000 years based on correlation of volcanic ash found in this unit (analysis by Andrei Sarna-Wojcicki, USGS).

Fault that ruptured in 1906 roughly parallels the western shore of Bolinas Lagoon. Their geologic maps show that the unsorted and poorly consolidated terrace gravels are offset along this strand of the San Andreas Fault. In addition, Pliocene- to Pleistocene-age marine and marine-terrace deposits (Merced Formation of Clark and Brabb, 1997) occur on the hillsides on the west side of the 1906 fault rupture.

The San Gregorio Fault (called the "west boundary fault trace" by Galloway, 1977) comes onshore on the east side of "downtown" Bolinas. The fault follows the linear trough of Paradise Valley before crossing into Olema Valley. Paradise Valley lies just to the west of Horseshoe Hill Road, which connects between Highway 1 and Bolinas. The fault scarp is expressed as a steep slope just east of the intersection of Olema-Bolinas Road and Mesa Road in Bolinas. Rocks on the east side of the fault are mapped as the Merced Formation, whereas rocks on the west side of the fault are mapped as Santa Cruz Mudstone.

Selected References

Anooshehpoor, A., Heaton, T.H., Shi, B., and Brune, J.N., 1999, Estimates of the ground accelerations at Point Reyes Station during the 1906 San Francisco earthquake: Bulletin of the Seismological Society of America, v. 89, no. 4, p. 845-853.

Barbour, M.G., and Major, J., eds., 1997, Terrestrial vegetation of California: New York, John Wiley and Sons, 1030 p.

Best, M.G., 1982, Igneous and metamorphic petrology: New York, W.H. Freeman and Company, p. 115.

Blake, M.C., Jr., Graymer, R.W., and Jones, D.L., 2000, Geologic map and map database of parts of Marin, San Francisco, Alameda, Contra Costa, and Sonoma Counties, California: U.S. Geological Survey Miscellaneous Field Studies Map 2337, 1 sheet, scale 1:75,000.

Brown, M. and Holzman, B., 1998, Point Reyes Peninsula and vicinity, ecosystem field trip: [http://www.sfsu.edu/~geog/bholzman/ptreyes/welcome.htm].

Brabb, E.E., Jones, D.L., and Wentworth, C.M., 1998, Regional relations of Paleocene and Eocene strata of the Gualala Block: AAPG Bulletin, v. 82, no. 5, p. 843.

Bruns, T.R., Cooper, A.K., Carlson, P.R., and McCulloch, D.S., 2002, Structure of the submerged San Andreas and San Gregorio Fault Zones in the Gulf of the Farrallones off San Francisco, California, from high-resolution seismic-reflection data, *in* Parsons, T., ed., Crustal structure of the coastal and marine San Francisco Bay region, California: U.S. Geological Survey Professional Paper 1658, p. 77-117.

Burnham, K., 1998a, The Point Reyes Conglomerate— a segment of the Carmelo Formation displaced 150 to 185 km by the San Gregorio Fault in west-central California: AAPG Bulletin, v. 82, no. 5, p. 843-844.

Burnham, K., 1998b, Preliminary comparison and correlation of two Cretaceous conglomerates, the strata of Anchor Bay and an unnamed unit in the Pilarcitos Block, across the San Gergorio and San Andreas Faults, *in* Elder, W.P., ed., Geology and tectonics of the Gualala Block, Northern California: Society of Economic Paleontologists and Mineralogists, Pacific Section [field-trip guidebook], Book 84, p. 95-119.

Burnham, K., 1999, Point Lobos, Comparison and correlation of Cretaceous and Paleogene rocks of Point Lobos and Point Reyes, *in* Garrison, R.E., Aiello, I.W., Moore, J.C., eds., Late Cenozoic fluid seeps and tectonics along the San Gregorio Fault Zone, central coastal California: Monterey, California: AAPG Pacific Section, Guidebook, p. 141-151.

Caughman, M., and Ginsberg, J.S, 1987, California coastal resources guide: San Francisco, California Coastal Commission, p. 141-153.

Clark, J.C., Brabb, E.E., Greene, H.G., and Ross, D.C., 1984, Geology of Point Reyes Peninsula and implications for San Gregorio Fault history, *in* Crouch, J.K. and Bachman, S.B., eds., Tectonics and sedimentation along the California margin: Society of Economic Paleontologists and Mineralogists, Pacific Section, Book 38, p. 67-86.

Clark, J.C., and Brabb, E.E., 1997, Geology of the Point Reyes National Seashore and vicinity, Marin County, California–a digital database: U.S. Geological Survey Open-File Report 97-456, 1 sheet, scale 1:48,000 [http://wrgis.wr.usgs.gov/open-file/of97-456/].

Clark, J.C., 1998, Neotectonics of the San Gregorio Fault Zone–age dating controls on offset history and slip rate: AAPG Bulletin, v. 82, no. 5A, p. 844-845.

Figure 9-48. Headlands and sea cliffs along Highway 1 (Shoreline Highway) south of Stinson Beach consist of mostly greenstone of the Franciscan Complex. Outcrops of chert, sandstone, and serpentinite can be seen in road cuts along the highway between Bolinas and San Francisco. This view is looking north along Highway 1 in a section of road prone to landslides. Headlands near Duxbury Reef at the west end of Bolinas Bay are in the upper left.

Galloway, A.J., 1977, Geology of the Point Reyes Peninsula, Marin County, California: California Division of Mines and Geology Bulletin 202, 72 p.

Gilbert, G.K., 1908, The San Francisco earthquake and fire of April 18, 1906: U.S. Geological Survey Bulletin 324, 170 p.

Gilliam, H., 1962, Island in time—the Point Reyes Peninsula: San Francisco, The Sierra Club, 87 p.

Grove, K. and Niemi, T.M., 1999, The San Andreas Fault Zone near Point Reyes—Late Quaternary deposition, deformation, and paleoseismicity, *in* Wagner, D.L. and Graham, S.A., eds., Geologic field trips in northern California: California Department of Conservation, Division of Mines and Geology, Special Publication 119, p. 176-187

Hobson, C., 1994, Shipwreck stories—facts & fictions: San Francisco, Pacific Editions [http://www.charleshobson.com/books/shipwreck.html].

Jachens, R.C., Wentworth, C.M., and McLaughlin, R.J., 1998, Pre-San Andreas location of the Gualala Block inferred from magnetic and gravity anomalies, *in* Elder, W.P., ed., Geology and tectonics of the Gualala Block, northern California: Society of Economic Paleontologists and Mineralogists, Pacific Section, Book 84, p. 27-63.

Jachens, R.C., Wentworth, C.M., Zoback, M.L., Bruns, T.R., and Roberts, C.W., 2002, Concealed strands of the San Andreas Fault system in the central San Francisco Bay region, as inferred from aeromagnetic anomalies, *in* Parsons, T., ed., Crustal structure of the coastal and marine San Francisco Bay region, California: U.S. Geological Survey Professional Paper 1658, p. 43-61.

Jordan, D.S., 1907, The earthquake rift of 1906, *in* Jordan, D.S., ed., The California earthquake of 1906: San Francisco, A.M. Robertson, 360 p.

Karl, H.A., Chin, J.L., Ueber, E., Stauffer, P.H., and Hendley J.W., II, 2000, Beyond the Golden Gate—oceanography, geology, biology, and environmental issues in the Gulf of the Farallones: U.S. Geological Survey Circular 1198, 78 p. [http://geopubs.wr.usgs.gov/circular/c1198/].

Lawson, A.C., 1895, Sketch of the geology of the San Francisco Peninsula, California: U.S. Geological Survey Annual Report, v. 15, p. 399-476.

Lawson, A.C., 1895, A contribution to the geology of the Coast Ranges: American Geologist, p. 342-356.

Lawson, A.C., 1914, Description of the San Francisco (California) districts: U.S. Geological Survey Geologic Atlas, Folio 193.

Nemi, T.M., and Hall, N.T., 1992, Late Holocene slip rate and recurrence of great earthquakes on the San Andreas Fault in northern California: Geology, v. 20, v. 3, p. 196-198.

National Oceanic and Atmospheric Administration, 2005, Gulf of the Farallones National Marine Sanctuary/Cordell Banks National Marine Sanctuary shipwreck database: [http://www.cinms.nos.noaa.gov/shipwreck/gfnms1.html].

National Park Service, 1996, Vision Fire: California, Point Reyes National Seashore [http://www.nps.gov/pore/fire_visionfire.htm].

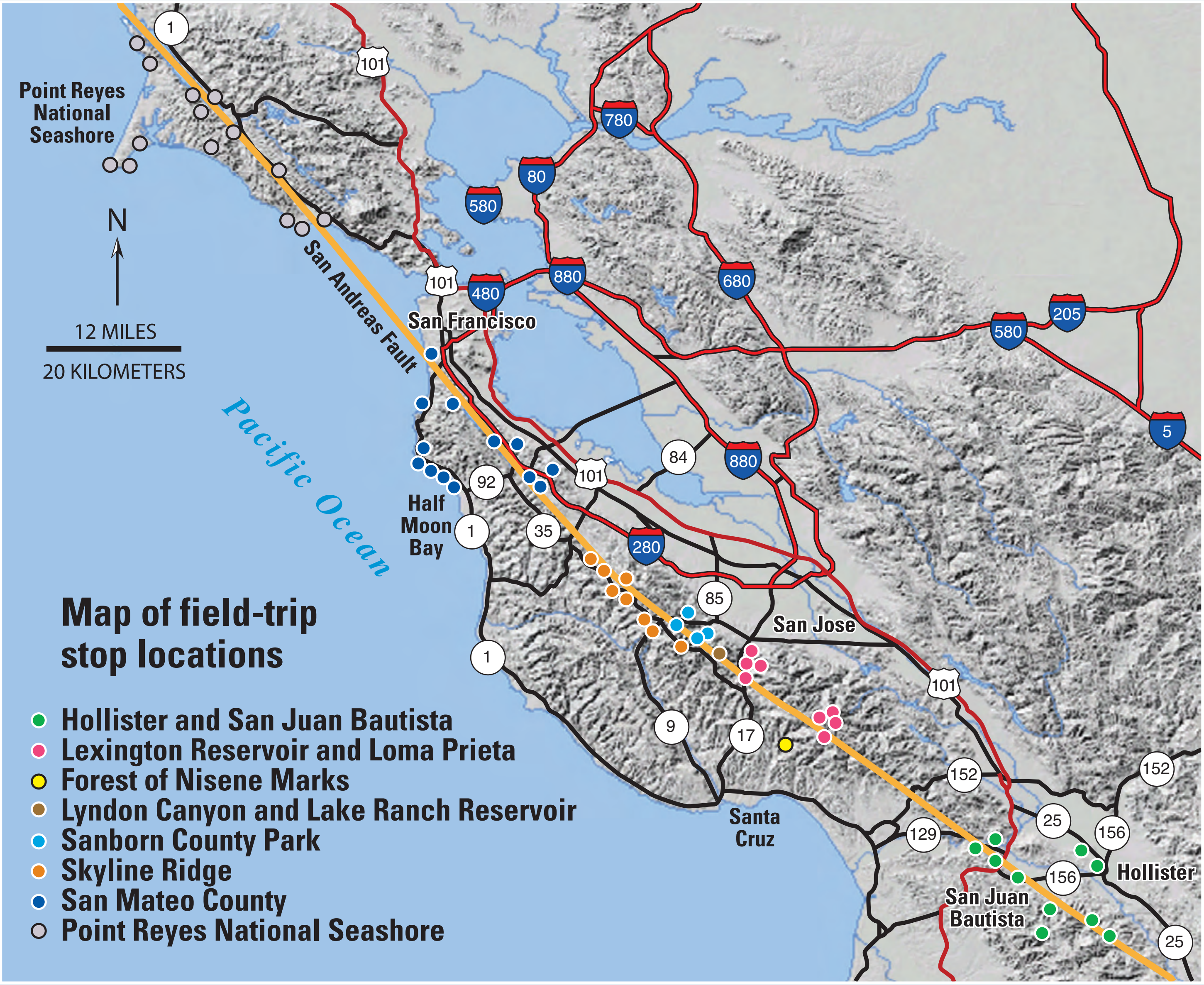
Ross, D.C., 1983, The Salinian Block—a structurally displaced granitic block in the California Coast Ranges, *in* Roddick, J.A., ed., Circum-Pacific plutonic terranes: Geological Society of America Memoir 159, p. 255-264.

Schulz, S.S. and Wallace, R.E., 1997, The San Andreas Fault: U.S. Geological Survey General Interest Publication: [http://pubs.usgs.gov/gip/earthq3/].

Sims, J.D., 1993, Chronology of displacement of the San Andreas Fault in central California—evidence from positions of exotic rock bodies near Parkfield, California, *in* Powell, R.E., Weldon, R.J., II, and Matti, J.C., eds., The San Andreas Fault system—displacement, palinspastic reconstruction, and geologic evolution: Geological Society of America Memoir 178, p. 231-256.

Stanley, R.G., and Lillis, P.G., 2000, Oil-bearing rocks of the Davenport and Point Reyes areas and their implications for offset along the San Gregorio and northern San Andreas Faults: Proceedings of the 3rd conference on tectonic problems of the San Andreas Fault system (September 6-8, 2000): Stanford University, extended abstract [http://pangea.stanford.edu/gp/sanandreas2000/Stanley.pdf].

Wentworth, C.M., Jones, D.L., and Brabb, E.E., 1998, Geology and regional correlation of the Cretaceous and Paleogene rocks of the Gualala Block, California, *in* Elder, W.P., ed., Geology and tectonics of the Gualala Block, northern California: Society of Economic Paleontologists and Mineralogists, Pacific Section, Book 84, p. 3-26.



Map of field-trip stop locations

ISBN 1-411-30971-5

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