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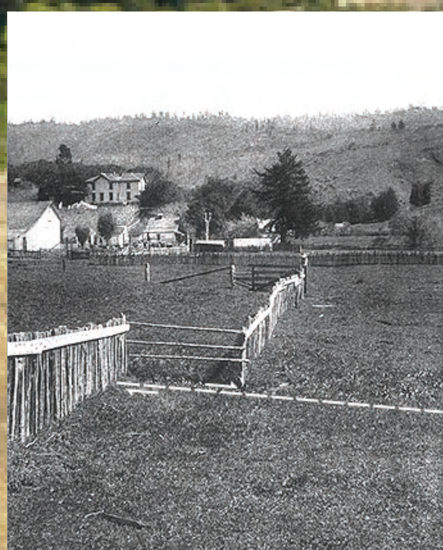
Where's the San Andreas Fault?

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
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By Philip W. Stoffer

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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
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

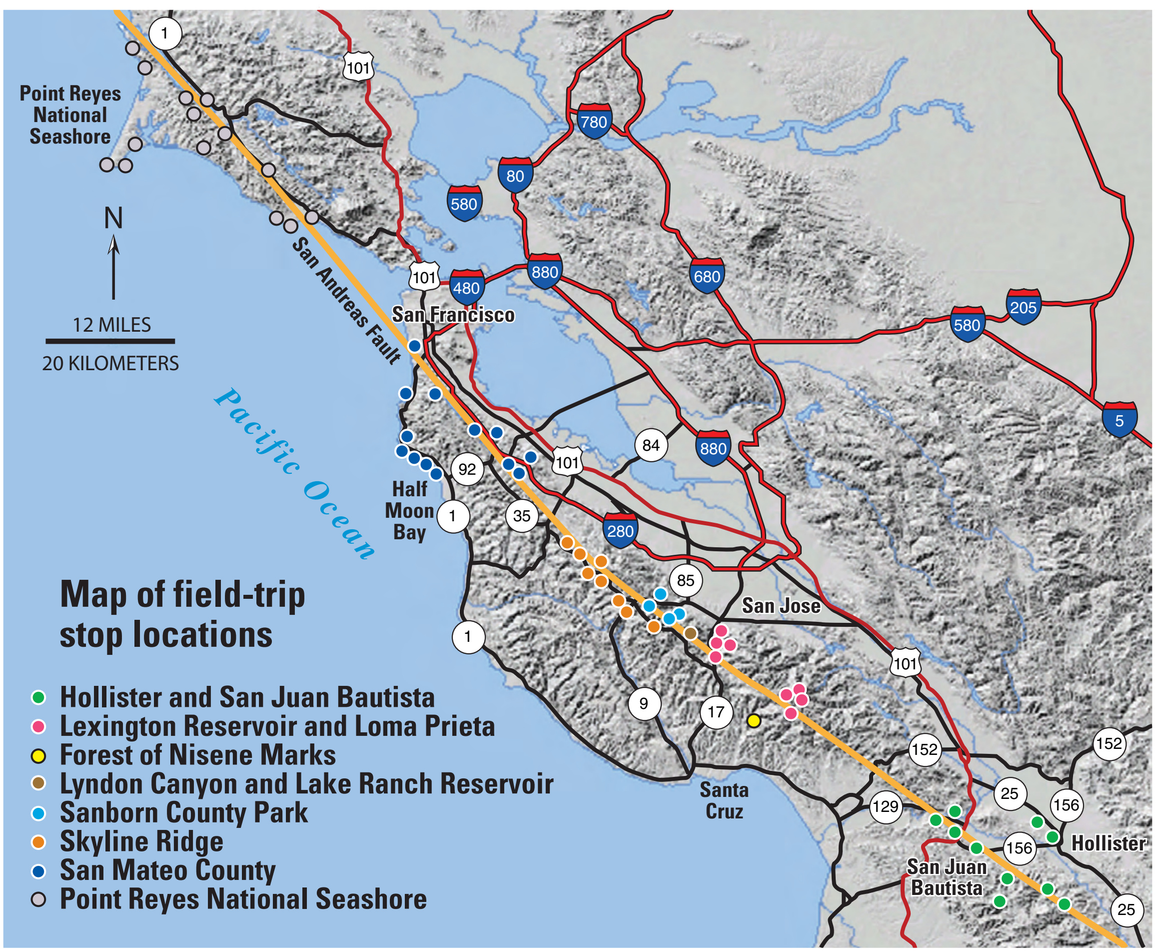


Figure 1-1. Map showing the field-trip destinations along the San Andreas Fault and vicinity. Small dots show the location of stops discussed in field-trip chapters. The orange line represents the San Andreas Fault section that ruptured in the earthquake of 1906.

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

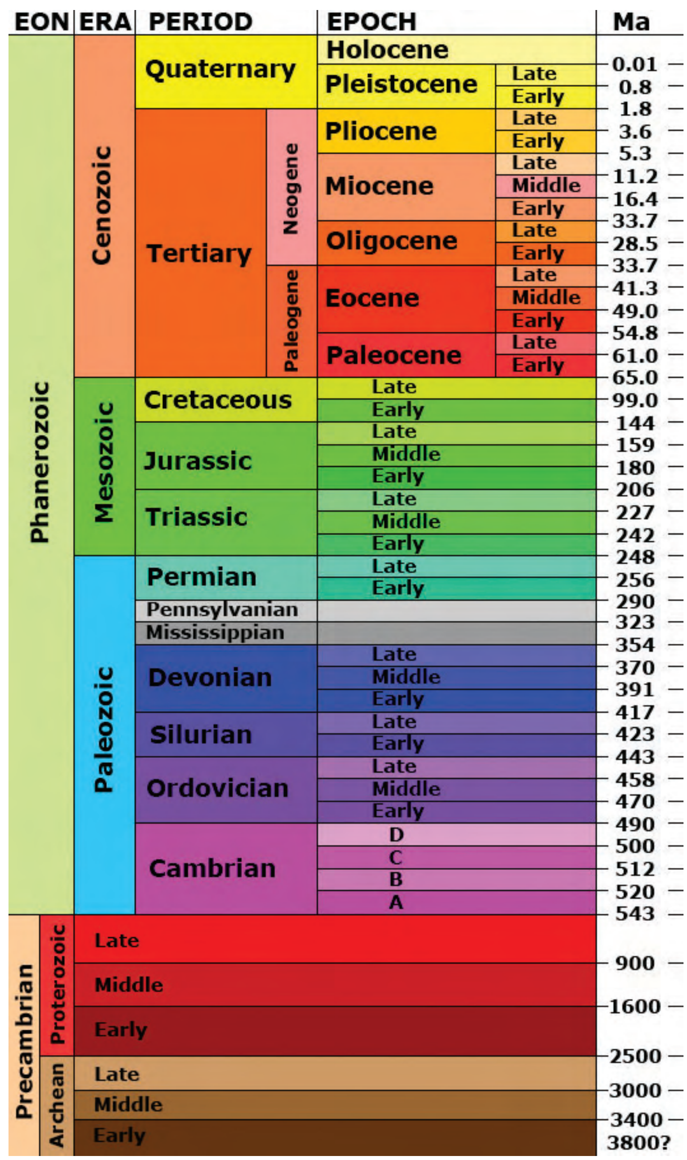


Figure 1-2. Geologic time scale. Time subdivisions and geologic ages in millions of years (Ma) are after the Geological Society of America 1999 Geologic Time Scale [http://www.geosociety.org/science/timescale/timescl.pdf].

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-

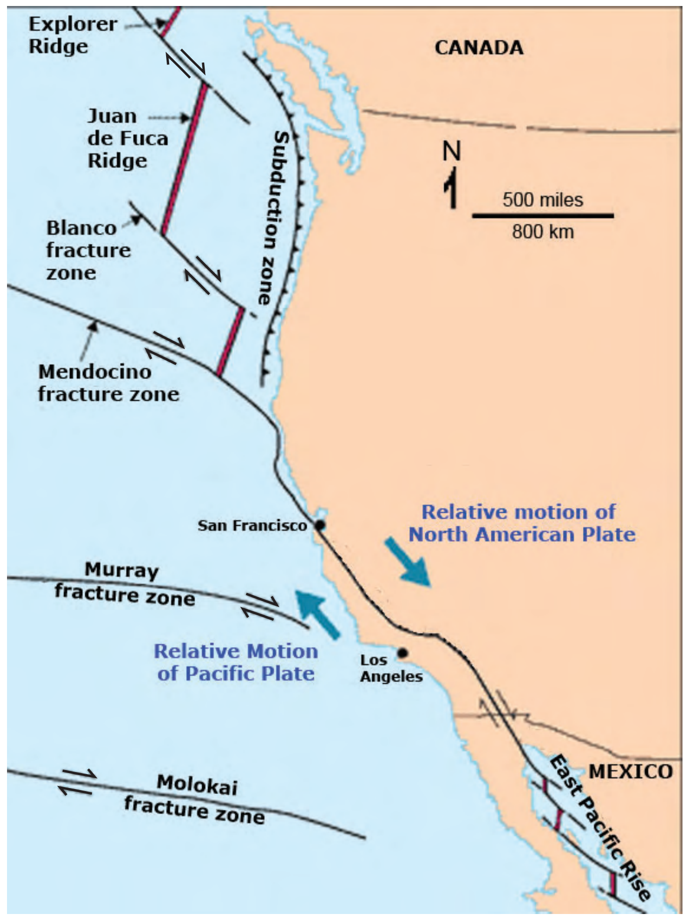


Figure 1-3. Map of the San Andreas Fault in relation to the greater plate-tectonic setting of western North America and the northeastern Pacific Ocean basin. The San Andreas Fault represents a great transform-fault boundary between the North American Plate and the Pacific Plate. The San Andreas Fault 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

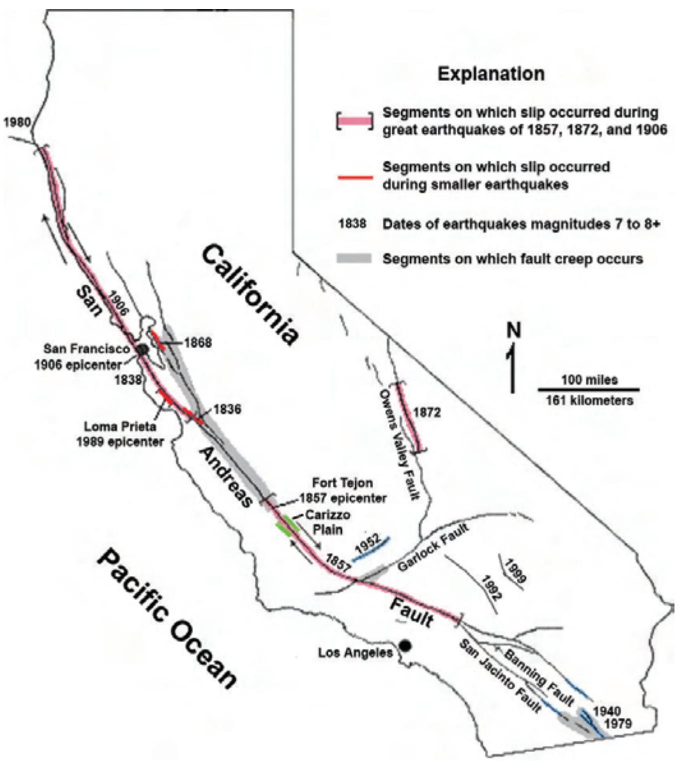


Figure 1-4. The San Andreas Fault system has a historical record of moderate to great earthquakes. The surficial expressions of the two greatest historical earthquakes on the San Andreas Fault are fairly well documented. The San Francisco earthquake of 1906 was similar in magnitude to the Fort Tejon 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.)

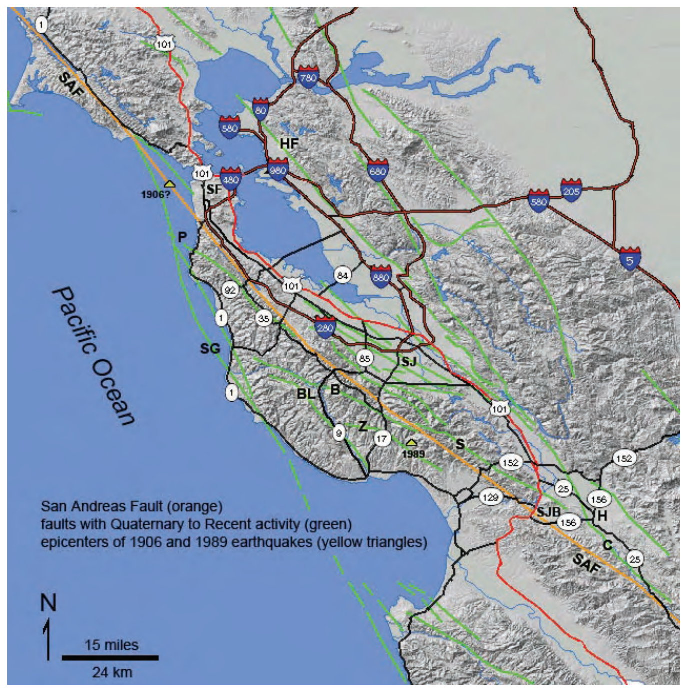


Figure 1-5. Map showing the trace of the San Andreas Fault (shown in orange) through the San Francisco Bay region. Additional faults that have had Quaternary-age and historical earthquake activity or movement are shown in green. The location of the epicenter of the 1989 Loma Prieta earthquake and the 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.

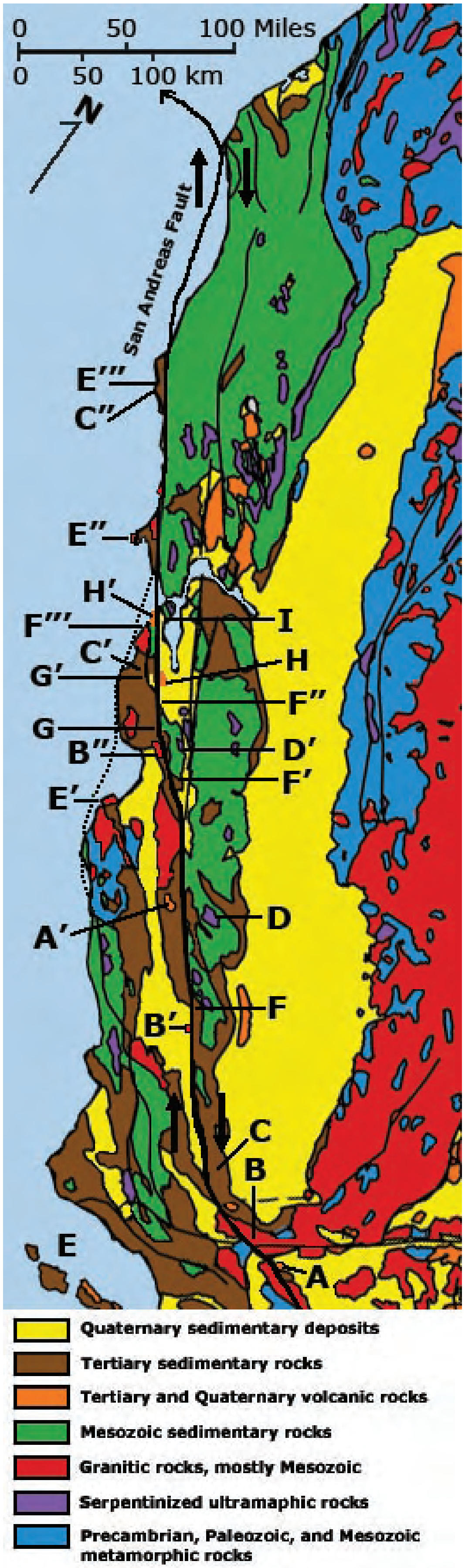
Rocks East of the Fault

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).

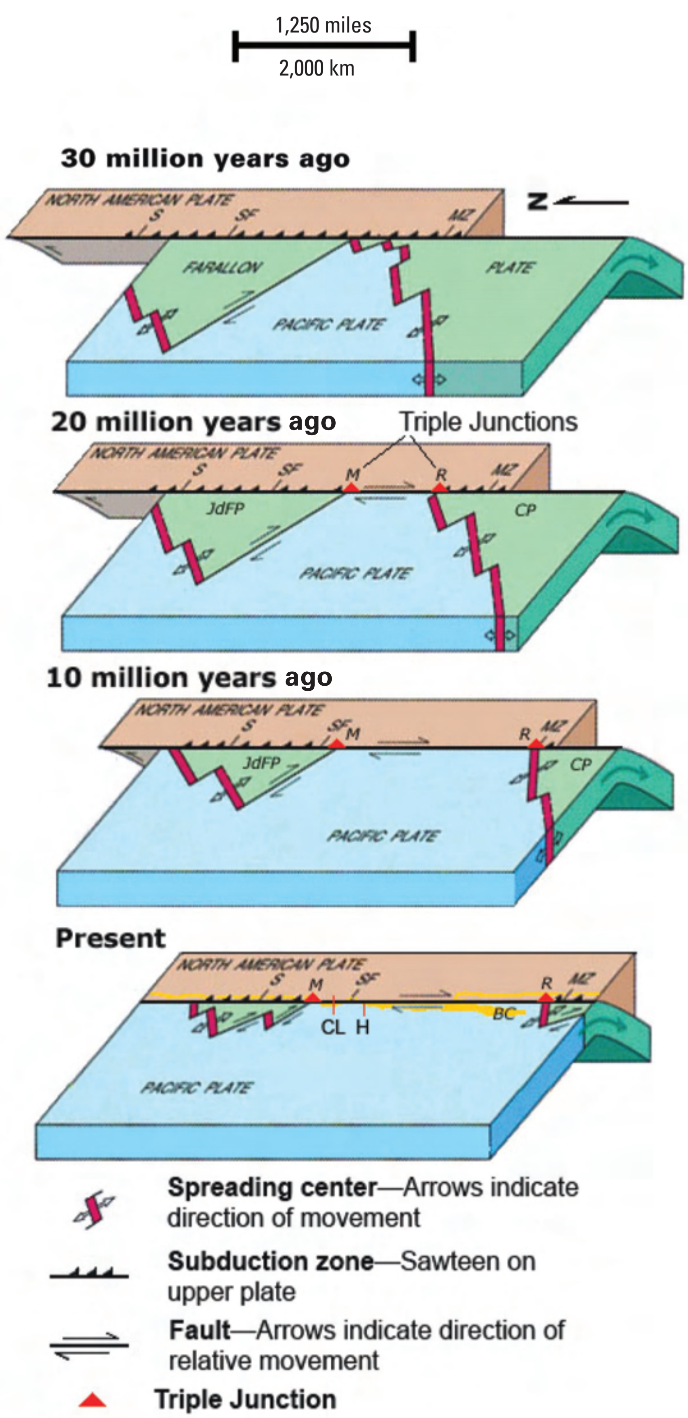
G, Gravels the Corte Madera facies of the Santa Clara Formation of Plio-Pleistocene age (3 to 1 million old) derived from the Loma Prieta and Mount Umunhum summit areas: G, Santa Clara Formation along Lexington Reservoir; G', Corte Madera facies in the Los Trancos and Monte Bello preserves area; G to 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:

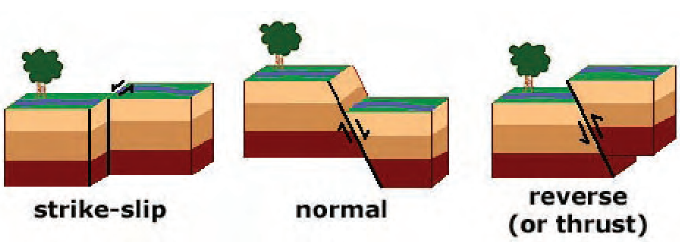


Figure 1-8. The strike-slip fault shown here displays right-lateral offset. Dip-slip faults include normal and reverse (or thrust) faults. Although strike-slip motion dominates, all three types of faulting and combinations of strike-slip and dip-slip can be observed along the San Andreas Fault and other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

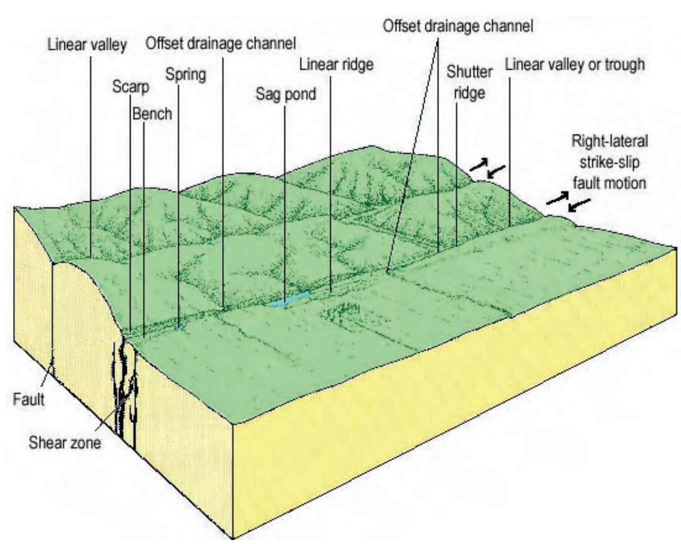


Figure 1-9. Geomorphic features associated with the San Andreas Fault system in California (after Vedder and Wallace, 1970).

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

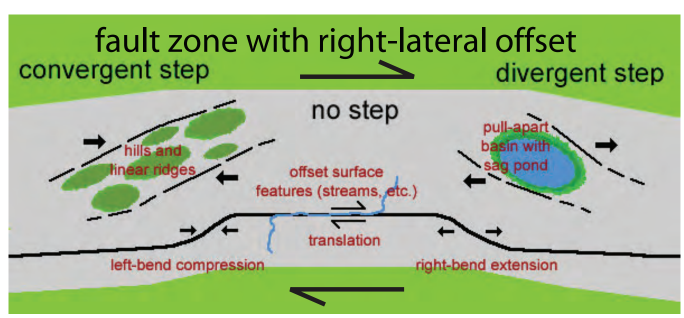


Figure 1-10. Geomorphic features associated with divergent and convergent step in a fault zone. Step faults are closely spaced, usually parallel faults over which the total displacement within a fault zone is distributed. Active faults (black) are shown within a broader fault zone (gray). These examples 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

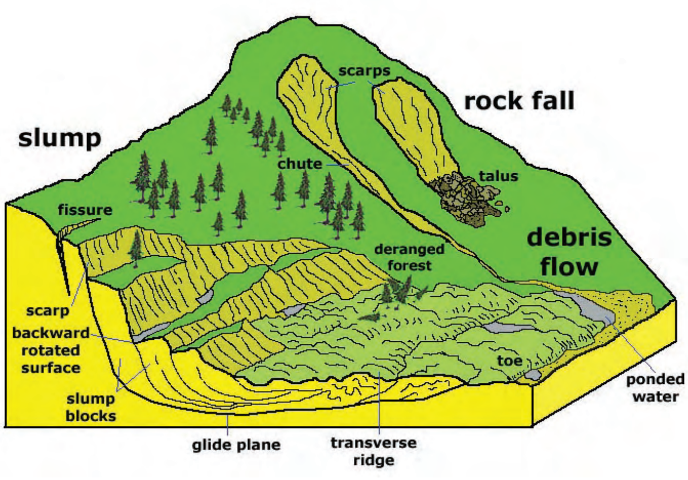


Figure 1-11. Landscape features associated with landsliding and slumping.

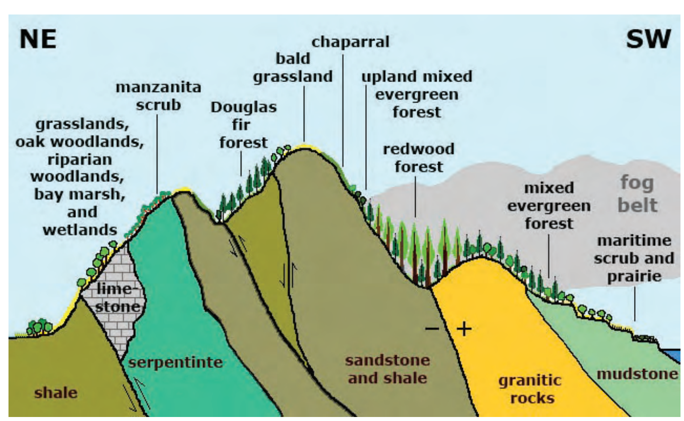


Figure 1-12. Plant habitats of the Santa Cruz Mountains. The diagram also shows the generalized bedrock character of the Santa Cruz Mountains. Arrows show thrust faults, and the –\+ designation shows the San Andreas Fault with its right-lateral offset (+ is toward the viewer; – is away). Note that vegetation 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

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.

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 1-20. 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.

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.

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.

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 1-22. 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 1-24. 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.

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