Geomorphology and Plate Tectonics

Photo: Mike Fuller

Landscape as Geological Expression

California's GeoGems exemplify the geologic legacy and processes that create the complex landscape and support the state's diverse habitats. According to eminent botanist Arthur Kruckeberg, "Geology is the supreme arbiter and creator of climate in California." Climate and geology work hand in hand to make landscapes. The study of landscapes from a geologic perspective is called geomorphology. California's landscapes result from usually slow, yet inexorable geologic processes that we are only beginning to understand. Some processes are so slow that in a human time frame nothing seems to be happening, yet at times change is disastrously rapid—as in earthquakes and landslides.

To sort things out, the state has been divided into eleven geomorphic provinces—regions of similar form and geologic origin, that are readily discernible even from space. Along California's 1,100 mile coastline, coastal landforms overprint the western boundaries of the geomorphic provinces that we define in this report as "coastline subprovinces." Within each province, the geologic materials or building blocks have been recycled from previous landscapes. Each province consists of something old and something new. The evolving landscapes within each province result from underlying—sometimes subtle, sometimes violent—geologic forces. The most potent geologic forces in landscape formation are explained by the theory of plate tectonics.

Geologic and Geomorphic Boundary Zones

The boundaries of the geomorphic provinces are not always as distinct as implied by lines on a large-scale map (Figure 2-1). Up close, they are often zones with miles of overlap. These boundary zones can be complex mixtures of provinces. Boundary zones are the intersections of contrasting geologic forces or environments and consequently much of the geologic evolution is recorded or best displayed at these boundary zones.

The scenic coastline of California extends nearly 1,100 miles and is another shifting geomorphic boundary. The pounding forces of the ocean beat against the land as it is exposed by geological processes. Nowhere else in California are the effects of global climate and geology so concentrated. Again, geology and climate create landscape. Even the effect of the moon's gravitational pull driving the tides is magnified as the waves shape the shore. Broad marine terraces, steep cliffs, sandy beaches, tide pools, and mud flats result depending on the ever-changing dynamics. The position of the shoreline changes with sea level which, in the past 11,000 years, has changed nearly 400 feet in elevation. In many places, that vertical change equates to miles of horizontal migration of the shore. For example, until 5,000 years ago, San Francisco Bay was just an inland river valley. Nowhere else in California is biodiversity so concentrated.

"Geology is the supreme arbiter and creator of climate in California."

Arthur Kruckeberg, botanist

Many of the boundaries are active and still evolving. They are a study of contrasts and of landscape evolution—often in earth shaking proportions. Boundary zones are scenic, interesting, and powerful places.

Faults

Another type of geologic boundary subdivides the state—cutting across geomorphic provinces—and continues to change the landscape, driven by plate tectonics. In simplest terms, the Earth's crust is broken into many plates—like a cracked egg shell. In active areas, the edges of individual plates grind and crush against each other. In the eye of an engineer, cracks in a surface are flaws or "faults." Geologists also use

Figure 2-1: Geomorphic provinces with major active faults in black. Note how the faults virtually define many province boundaries.

that term; however geologic faults are not necessarily defects. They are boundaries along which adjoining sections of the earth's crust move. Earthquakes are, of course, the abrupt result of such movements. Tension gradually builds; then suddenly releases in a jolt. In human terms, they can be disasters. In the view of landscape formation, these are growing pains—construction not destruction.

Plate Boundary—the Leading Edge of the Continent

The history of the plate boundary goes back about two hundred million years to the time of the "supercontinents." At that time, all of the continents were amalgamated into one supercontinent that geologists have named Pangaea. Some of California's oldest rocks formed as oceanic sediments on the continental shelf of Pangaea. Over time, the supercontinent broke into smaller continents riding different plates that migrated to their current configurations. Sediments deposited in that very ancient sea along the continental shelf can now be found as limestone blocks (with fossils of ancient sea life) scattered along the western Sierran foothills, in the Coast Ranges, the Klamath Mountains, and north of the Sierra Nevada.

The longest faults lie along the boundaries between the large plates. Between the Salton Sea near Mexico and the Mendocino triple junction near Oregon, the infamous San Andreas Fault system is the major set of structures constituting the modern boundary between the gigantic plate that underlies the Pacific Ocean (the Pacific plate) and the massive plate that underlies the North American continent (the North American plate). In Figure 2-1, the San Andreas Fault system can be seen as a series of parallel faults running through the Colorado Desert and the Coast Ranges. The two plates are grinding along their edges as the Pacific plate slides towards Alaska, creating a right lateral shear. Right lateral shear means an observer on the North American plate facing the west would see the Pacific plate is moving to the right.

The San Andreas Fault system accommodates approximately 75% of the right lateral shear. North of the Salton Sea in the Colorado Desert Geomorphic Province, the remainder of shear occurs along the western boundary of the Basin and Range province. In Figures 2-1 and 2-6, that boundary zone can be seen as swaths of faults that 1) bisect the Mojave Desert, 2) run along the eastern side of the Sierra Nevada, and 3) run across the northeastern corner of the state. Along this secondary shear zone, all of California is slowly being pulled in a more northerly direction than the rest of the North American continent.

Essentially, California straddles the continent's dynamic plate boundary. Similar to province boundaries but on a much larger scale, the plate boundary can be a very broad zone. Prominent geologist Deborah Harden wrote, "The complexities of California geology are revealed when one realizes that even the question 'Where is the exact boundary between the Pacific and North American plates?' has no precise answer." Caution: the landscape of California is constantly undergoing remodeling and the plate boundary is the construction zone.

Each geomorphic province tells a separate tale of what happens along an active plate boundary. Each province is a piece of California's tectonic jigsaw puzzle. The following overview of plate tectonics provides a view of the big picture of California's geologic heritage.

Plate Tectonics Overview

The earth's crust is cracked like the shell of a hard-boiled egg. Each major piece of cracked crust is called a tectonic plate (Figure 2-2). The earth's crust is constantly shifting, albeit very slowly, from millimeters to centimeters per year. Over the course of a hundred million years that equates to hundreds to thousands of kilometers of movement. Beneath the crust is a hot ductile layer of the upper mantle called the

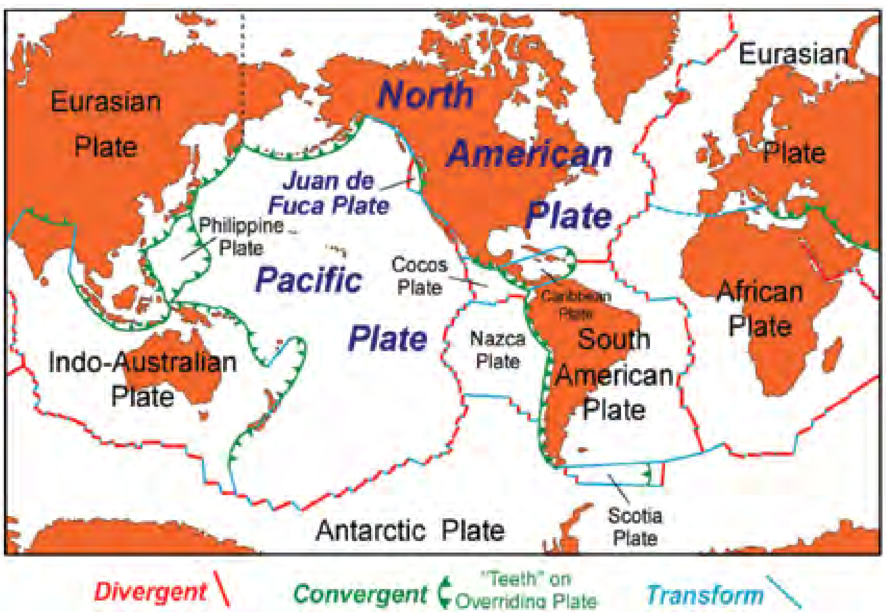

Figure 2-2: Tectonic plates and boundary types (Lillie, 2005).

asthenosphere (Figure 2-3). As two adjacent plates move across the asthenosphere, they either collide, slide past another, or separate. The study of how these plates move and interact and the consequences thereof is called plate tectonics from the Greek word, tekton, which means builder. The continents ride as passengers on large plates. The enormous energy and momentum of shifting plates is focused along their active margins like California.

The crust that underlies the oceans differs from the continental crust. Oceanic crust is typically much younger, thinner, and denser than the continental crust. This is due

Interior of the Earth by Strength

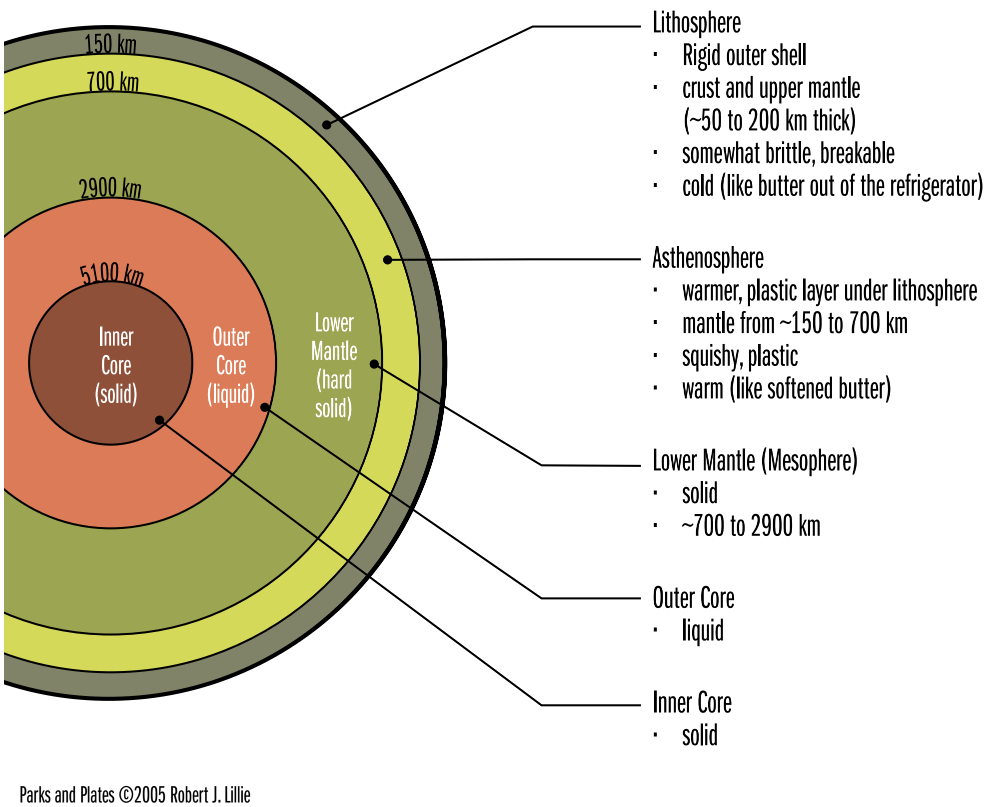

Figure 2-3: Layers of the earth (Lillie 2005). The crust is the outermost part of the lithosphere

to very different processes of formation. Oceanic crust is formed where two oceanic plates separate. The influx of molten magma into the gap solidifies to form new crust, often as a ridge. Locations of spreading are referred to as either spreading centers or spreading ridges. As the plates continue to diverge and new crust is added, the plates grow. Because the surface area of the globe is relatively fixed, for there to be room for oceanic plates to grow, somewhere plates must also be destroyed. This happens at convergent margins where plates collide. One of the plates either overrides the other or dives down (subducts) into the asthenosphere where it melts. Zones of subduction can be thought of as places where oceanic crust is melted and recycled (Figure 2-4).

The crust floats upon the asthenosphere because of buoyancy. Continental crust is less dense, more buoyant, and thicker than oceanic crust and so tends to override oceanic plates during tectonic collisions. Over the long term, the oceanic plates sink (or subduct) into the asthenosphere where they partially melt.

Continental crust is formed in subduction zones. As the descending oceanic plates partially melt, the melt rises as magma. Eventually, the magma either solidifies against (underplates) or within the cool continental crust, or penetrates along

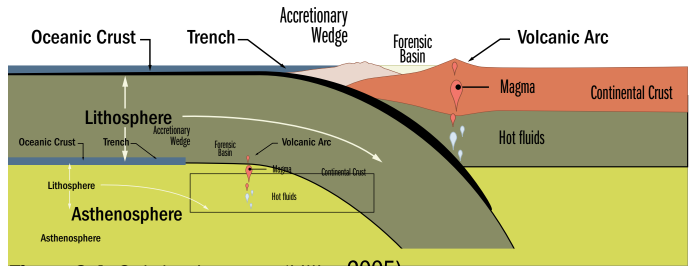

Figure 2-4: Subduction zone (Lillie, 2005).

fractures upward to erupt on the surface as lava and ash. Continental crust grows in another mechanism related to subduction processes. In what could be viewed as failed subduction, oceanic crust and sediments (instead of subducting) amalgamate (accrete) against the leading edge of the continent and are fused through compression, metamorphism, intrusion, and underplating.

As seen in Figure 2-2, divergent plate margins have a distinctive zigzag pattern. Fractures develop along spreading ridges with regular perpendicular offsets. The offsets are fractures that allow adjacent portions of the ridge to slide past each other. These fractures accommodate variable rates of spreading and crust production over the earth's curved surface. Where long portions of plate margins slide sideways along such fractures they are called transform faults. The complex and irregular margins of major plates can result in the creation of isolated fragments (smaller plates) as subduction proceeds. The presence of smaller plates, like the Juan de Fuca and Cocos plates off the Pacific Coast of North America, are clues of a larger pre-existing Farallon plate which was subducted underneath the North American plate. Prior to 20 million years ago, subduction and partial melting of the Farallon plate resulted in a chain of volcanoes that rimmed North America's western edge (Figures 2-4 and 2-5).

The forces of colliding or rubbing plates can deform the crust hundreds of miles inland of the margins. As the motion of each plate shifts, even subtly, the zones of stress and deformation migrate accordingly. The crust deforms either in a brittle or ductile fashion or some combination. If brittle, it fractures and slides; if ductile, it folds and flows. If buried deep enough, it softens, partially melts, or melts to become molten magma. As with hot air, hot crust and hot magma rise along fractures and may vent at the surface in the form of volcanoes.

With the breakup of the supercontinent Pangaea hundreds of millions of years ago, the North American plate changed directions in a fundamental way. At that time, the North American and Eurasian continents were joined, but due to a major readjustment of plate motions, the continents rifted apart, with the North American plate moving westward. The rift grew to become the Atlantic Ocean. This change in direction caused the North American plate and the predecessors of the Pacific plate to collide head-on along the western margin of North America. As the collision progressed, the North American plate began to ride over the oceanic plate while the oceanic plate was pushed down (or subducted) deep into the hot earth where it began to melt.

A subduction zone is thought to have formed in what is now the foothills of the Sierra Nevada. The melting slab produced magma bodies that formed the plutons and huge batholiths that eventually solidified into what is now the Sierra Nevada. Prior to solidification, the batholiths fed magma to volcanoes atop the ancient Sierra Nevada that have since eroded away along with several miles of intervening rock. Like a gigantic plow, the North American plate scraped against the top of the oceanic plate and peeled off layers of sediments, islands, and seamounts. In places, large chunks of the oceanic plate broke off. These fragments which contain sediments deposited in the deep ocean together with volcanic rocks from the spreading ridge and pieces of the oceanic crust are collectively referred to as ophiolites. Scraped and broken pieces of ophiolite were plastered against the tectonic plate's leading edge and accreted to the continent. This is sometimes referred to as the Foothill Terrane, which contains a large section of ophiolite called the Smartville Ophiolite. These rocks are well-exposed in and surrounding **South Yuba River State Park.**

About 140 million years ago, the zone of subduction moved westward toward the area of today's Coast Ranges as material accreted. The Farallon plate was caught in the crush between the North American and Pacific plates. Crustal spreading occurred at a rift zone (the East Pacific Rise) along the boundary with the Pacific plate. The spreading drove the Farallon plate eastward to the encroaching North American plate and the subduction zone while the Pacific plate moved to the northwest. For reasons not well understood, mountain building then shifted to the Rocky Mountains in what is called the Laramide Orogeny. Oceanic terranes continued to accrete along the subduction zone and are found in parts of the Coast Ranges. These rocks are well-exposed at **Point Sal, Mount Diablo, Patrick's Point,** and **Del Norte Coast Redwoods State Parks.**

The subduction zone formed a deep offshore submarine trench into which sediments from adjacent uplands accumulated (Figure 2-4). The trench sediments were subducted enough to slightly metamorphose. The Franciscan Complex revealed in several of the GeoGems represents the trench sediments (Figure 2-5). The crust underlying almost all of California was accreted in this fashion. California has been stitched to the North American continent over the past 200 million years. Simply put, all of California was either formed or deformed by the forces along the active tectonic plate margin.

About 20 million years ago, the plate motions adjusted again but not as dramatically as before. The Pacific plate shifted to a northwesterly course and both literally and figuratively, "things went sideways." This shift transformed the head-on collision to more of a glancing, sliding blow. The sliding margin became what is referred to as the San Andreas Fault system which includes many faults

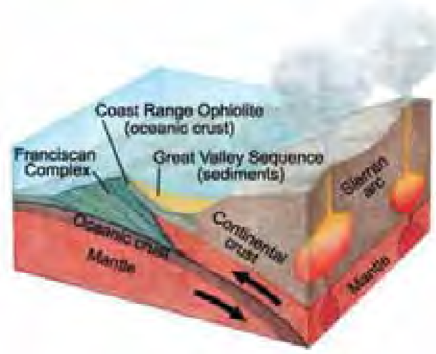

Figure 2-5: Subduction zone along California (Lillie, 2005)

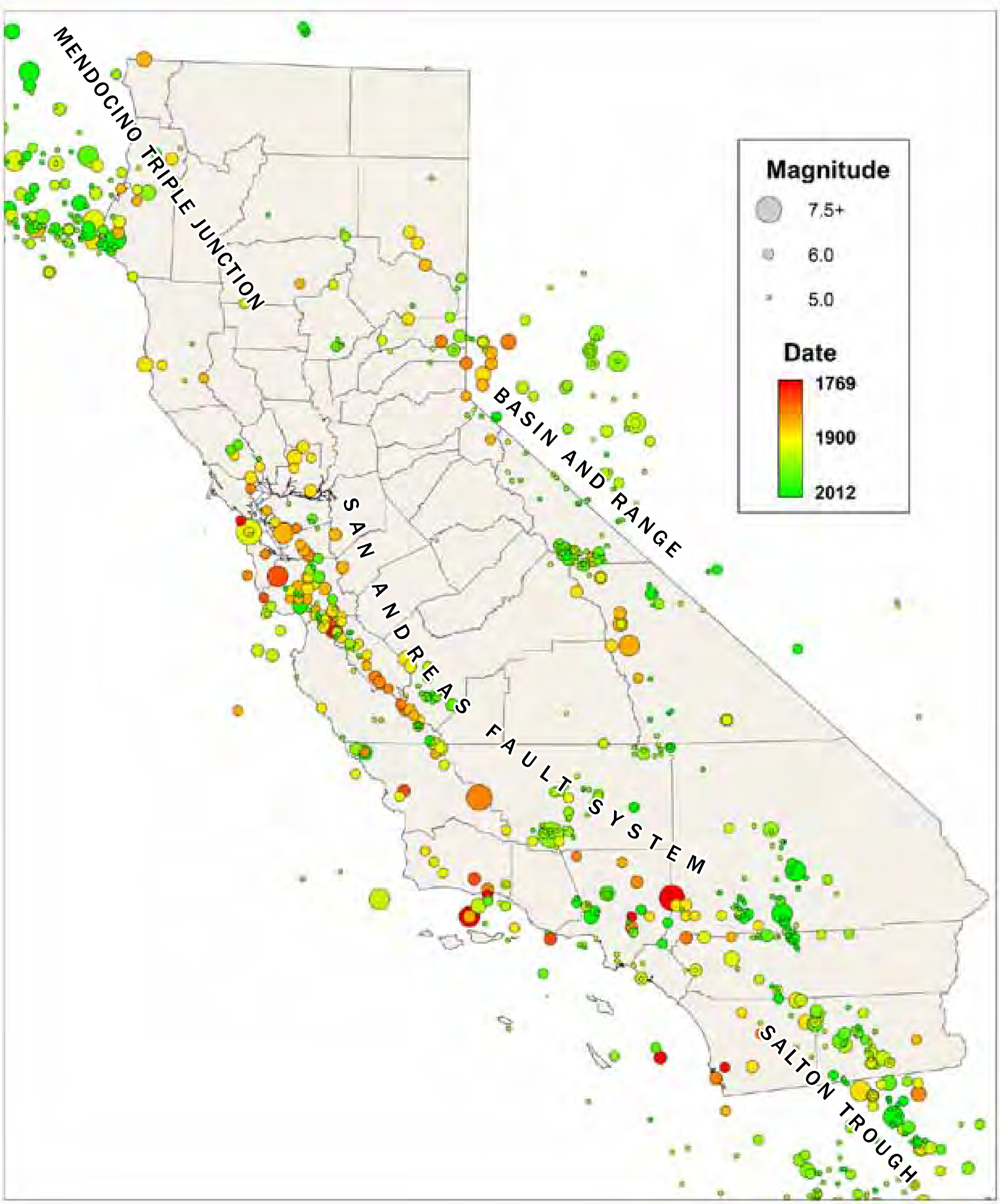

Figure 2-6 Historic Earthquake Epicenters: Clusters of earthquakes define the seismically active areas of California. Circles represent the locations of historic earthquakes. The size of the circle corresponds to the magnitude of the earthquake while the color indicates the general time period that the earthquake occurred. Compare the distribution of the earthquakes with the fault map, Figure 2-7.

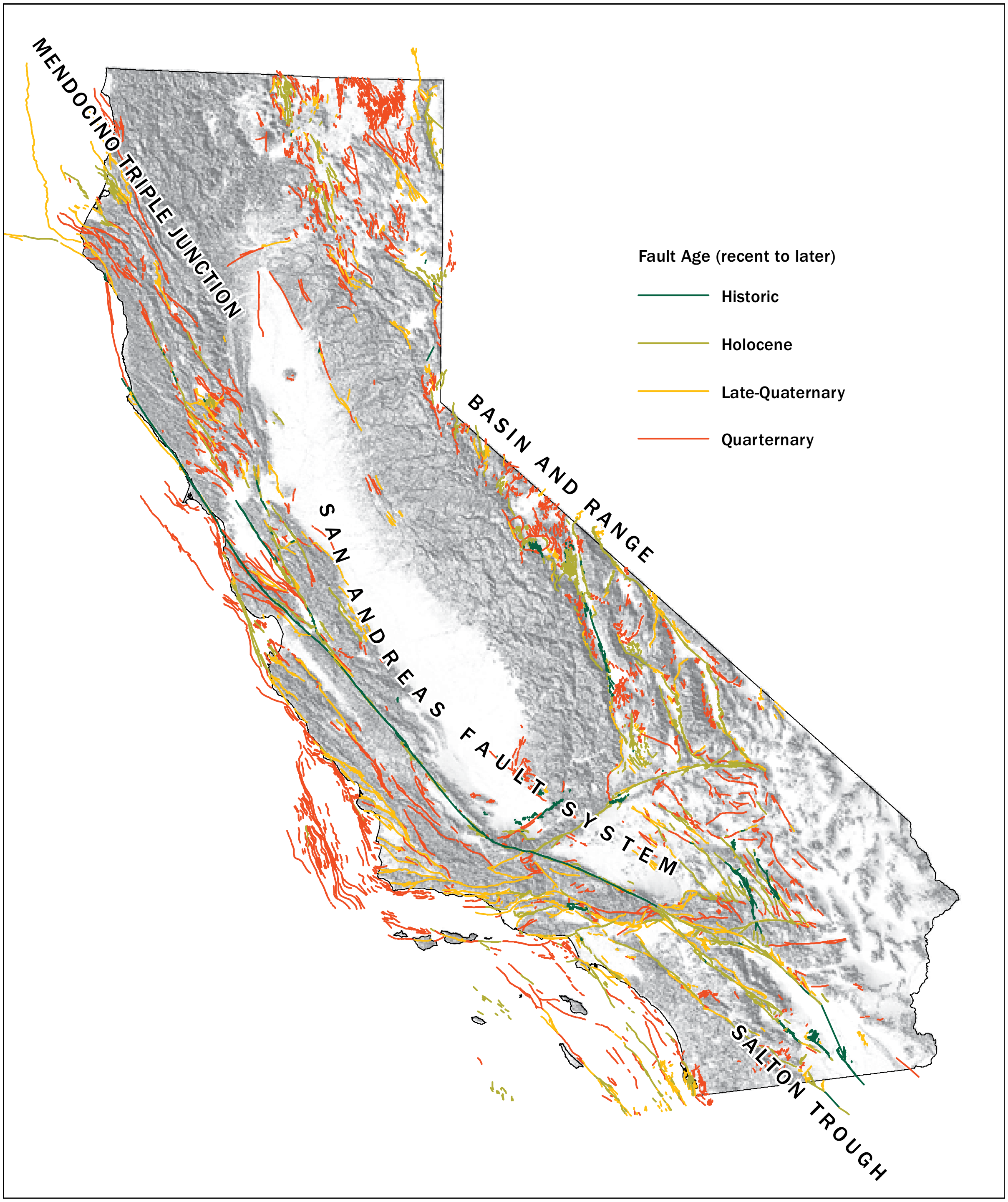

Figure 2-7 Fault Activity Map: Faults that experienced earthquakes either historically or during the Holocene are considered to be geologically active.

besides its famous namesake. Lands west of the San Andreas Fault system are part of the Pacific plate; those to the east belong to the North American plate. With plate boundaries being so significant in the geologic history, it seems fitting that the birthplace of the mighty San Andreas Fault system was at the intersection of three plate boundaries—a triple junction.

Triple Junctions

What is a triple junction? It is simply the place where three tectonic plates meet. As explained previously, in the case of an active margin between two plates, the energy and deformation is focused in a linear zone along the boundary. However, in the case of an active triple junction, the focus of energy and deformation is amplified in a region around the point of intersection. In terms of plate tectonics, triple junctions are one of the most actively deforming locales in the world—most of which are undersea.

In California, near the northern end of the San Andreas Fault, lies an active triple junction. The Mendocino triple junction is one of the most seismically active places in the state (Figure 2-6). Here the North American plate meets two adjoining oceanic plates, the actual Pacific plate and the Gorda plate, a fragment of the Juan de Fuca plate (Figure 2-2). Instead of being a precise point, the triple junction is a broad region of rapid geological change, which is covered with thick forests, landslides, and partly under the ocean.

The margin between the Gorda and Pacific plates runs east-west. The two plates slide sideways along their margin. As mentioned, the San Andreas Fault system is a sliding—sometimes grinding—plate margin and runs northwesterly and somehow merges into or terminates in the region of the triple junction. North of the triple junction, the boundary between the Gorda plate and the North American plate is the north-trending Cascadia subduction zone where North America continues to drive over the oceanic plate and to feed magma to the Cascade chain of volcanoes.

Formation of the San Andreas Fault System

Prior to 20 million years ago, a spreading ridge separated the Farallon and Pacific plates. While the Farallon plate progressively subducted, the Pacific plate and intervening ridge approached the North America continent. The ridge system was locally offset and generally oblique to the subduction zone. Because of the geometry (Figure 2-8) and motion between the plates, a portion of the ridge moved into the subduction zone. At this location—million years ago, subduction ceased and the North American and Pacific plates made contact. This event marked the birth of a triple junction. This contact essentially divided the Farallon plate into two smaller plates, the Juan de Fuca and Cocos plates. The new triple junction marked the point where the two new plates and the Pacific plate met. However, it was short-lived. As subduction

Figure 2-8: Progressive development of the San Andreas Transform Fault (Lillie, 2005).

continued the area of contact between the Pacific and North American plates lengthened. What was a single triple junction split into twins, joined by an incipient "transform" fault, the proto-San Andreas Fault.

The transform fault lengthened and the twin triple junctions separated farther. The growth of the proto-San Andreas created a gap (or window) where there was no subducting plate (or slab). The path of the northward migrating triple junction (Mendocino triple junction) is delineated by the San Andreas Fault. A sequence of volcanic fields that is progressively younger to the north may be the surficial expression of a progressive upwelling of fluid asthenosphere into the enlarging slab window with attendant melting of the overlying crust and volcanism. In the southern Coast Ranges, the volcanic fields are located along the San Andreas trace. North of San Francisco Bay, the volcanism is closer to the eastern splays of the San Andreas Fault system, which include the Rodgers Creek, Bartlett Springs and Collayomi Faults. The Clear Lake volcanic field, home of **Clear Lake State Park,** and the Sonoma volcanics, as seen in **Robert Louis Stevenson State Park,** are the youngest expressions of volcanism in this sequence.

Continental rocks west of the San Andreas Fault (Figures 2-6 through 2-8) became "stranded" on the Pacific plate, which continues to slide along the plate boundary to the northwest. Two bodies of continental rock thus accreted to the Pacific plate are the so-called "Salinian block" or "Salinia" and the Peninsular Ranges in Southern California. After several million years of sliding, a block of continental crust (possibly a southern continuation of the Sierra Nevada) was snagged by the passing Pacific plate and began to rotate clockwise. After more than 15 million years of sliding, the rotating block became the Transverse Ranges. Salinia was dispersed along northern California. Pieces of Salinia are exposed at **Salt Point State Park** and **Point Lobos State Natural Reserve.**

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for California State Parks | www.parks.ca.gov

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