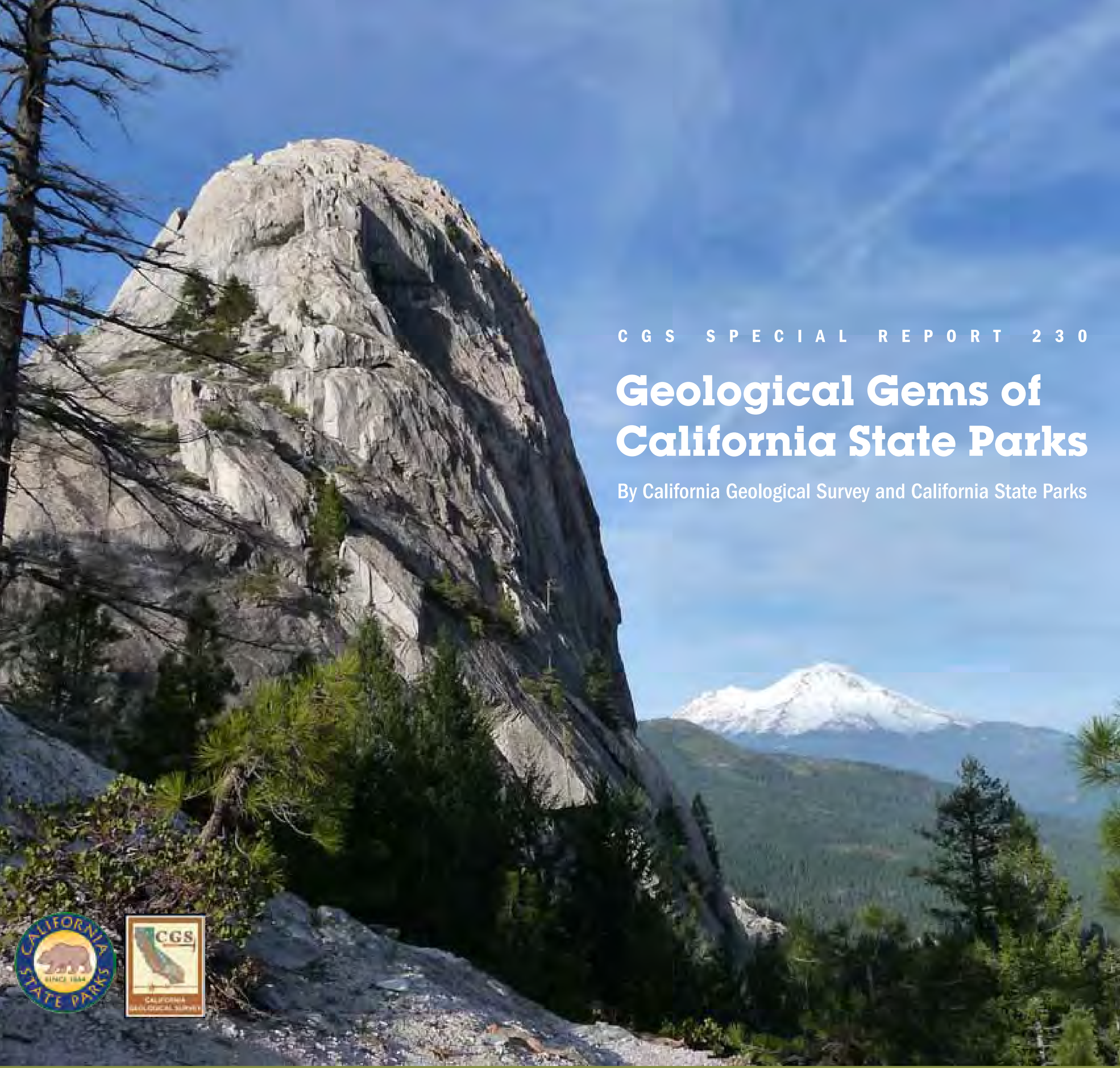

CGS SPECIAL REPORT 230

# Geological Gems of California State Parks

By California Geological Survey and California State Parks

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**Natural Resources Agency**
**John Laird, Secretary**

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2015

## SPECIAL REPORT 230

Copies of Geological Gems of California State Parks, and other related information are available at www.conservation.ca.gov/cgs.
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## COVER PHOTOS

Castle Crags State Park (center top), photograph by Chris Mizeur; Schooner Gulch State Beach (lower left), photograph by Jennifer Lotery; McArthur-Burney Falls Memorial State Park (lower center), photograph by Michael Wopat; Red Rock Canyon State Park (lower right), photograph by Mike Fuller.

This document has been prepared as a series of flyers that can be printed individually and distributed freely at visitor centers and other venues.

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# Table of Contents

# Introduction

California is a veritable treasure chest of nationally acclaimed natural landmarks and much adored scenery. This geologic legacy on display in the landscape can be observed throughout California's State Park system. The mission of California State Parks is "to provide for the health, inspiration and education of the people of California by helping to preserve the state's extraordinary biological diversity, protecting its most valued natural and cultural resources, and creating opportunities for high-quality outdoor recreation."

**This abundant biodiversity … everything from the alpine to the saline.**

We selected exemplary units of the State Park system to highlight California's geologic legacy. The selected parks are dubbed "GeoGems." Of these, a third have been bestowed various national accolades and recognitions. This GeoGem Note 1 is the first in a series of more than 50 notes that describe individual GeoGems, the geomorphic provinces in which they exist, and the processes that created them, leading off with a general explanation of plate tectonics in relation to the geomorphic provinces.

California's topography is one of the most diverse in the conterminous United States, including a splendid coastline; the largest estuary on the west coast; the famously fertile Great Valley; formidable mountain ranges studded with jewel-like lakes; parched, desolate deserts; snow-capped volcanoes; and extensive plateaus of lava. Elevations are extreme, ranging from 282 feet below sea level at Badwater in Death Valley to 14,495 feet above sea level at the top of Mount Whitney; both the lowest valley and the highest peak in the conterminous United States are less than 90 miles apart.

**Both the lowest valley and the highest peak in the conterminous United States are less than 90 miles apart.**

Along with complex landscape comes rich habitat diversity. California inherited the most diverse flora in the country; including majestic, ancient redwood and sequoia forests; kelp forests teeming with life; and grasslands and wetlands that support the famous Pacific Flyway—the main lifeline for migratory birds in western North America. This abundant biodiversity results from habitat heterogeneity (diversity), everything from the alpine to the saline. California's annual precipitation ranges from less than two inches in Death Valley in the south to over 100 inches at Honeydew in Humboldt County in the north. The abundant rainfall in the north feeds the many coastal streams that are the lifelines for the migratory Pacific salmon. Throughout an inland network of thousands of miles of streams, the life cycles of these anadromous fish both begin and end.

## GeoGem Parks with Special Recognition

### National Natural Landmarks

Anza-Borrego Desert State Park (1974)
Emerald Bay State Park (1968)
McArthur-Burney Falls Memorial State Park (1984)
Mount Diablo State Park (1982)
Mitchell Caverns in Providence State Recreational Area (1975)
Point Lobos State Natural Reserve (1967)
Torrey Pines State Natural Reserve (1977)
San Felipe Wash in Ocotillo Wells SVRA (1974)
Pygmy Forest in Jug Handle State Natural Reserve (1969)
Point Sal State Beach (1974)

### World Heritage Site

Redwood National and State Parks
includes Del Norte Coast Redwoods State Park

### International Biosphere Reserve

Redwood National and State Parks
includes Del Norte Coast Redwoods State Park

### National Estuary

Morro Bay State Park

### State Estuary

Morro Bay State Park

### State Wild and Scenic River

South Yuba River State Park

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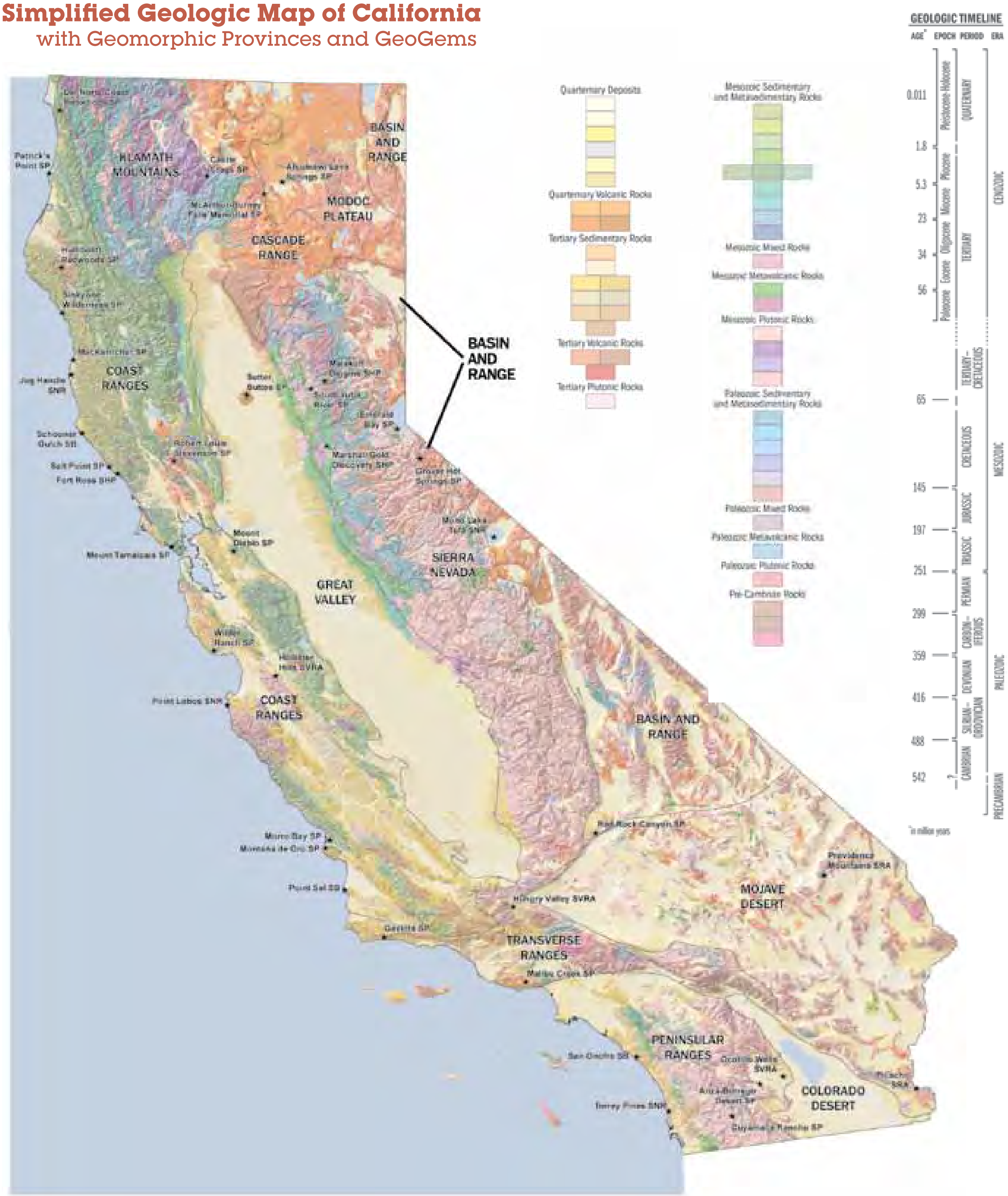
The great heterogeneity of habitat types supports California’s rich biodiversity. Biodiversity is a sign of a healthy ecosystem—one with a diverse portfolio. Biodiversity means adaptability to environmental changes such as climate change. Some of California’s habitat types are very fragmented, patchy, or of very limited distribution. These fragmented or small areas are more sensitive to change and may require special protection. For example, development has reduced the acreage of wetlands that comprise the Pacific Flyway by 91%, and many streams have been dammed or otherwise impacted by land-use practices. It is estimated that 90% of California’s original stream network is now cut off from salmon due to barriers or impaired habitat conditions.

With this set of GeoGem Notes, readers will better understand the richness of our geologic heritage that is the canvas upon which our scenic landscapes are painted. The interrelatedness of geology, biology, ecology and human life—past and present—clearly shows that we share a common future.

This document has been prepared as a series of flyers that can be printed individually and distributed freely at visitor centers and other venues. In addition to these notes, we have prepared a poster (Plate 1), a statewide map that introduces the GeoGems and delineates and explains both biological regions and geomorphic provinces. Due to its large size, hardcopies of the poster must be printed separately; however, it is viewable in the digital version of this note. From Plate 1, one can appreciate the intricate connections between geology and biology, and see where each GeoGem fits into California’s complex landscapes.

*Written by Mike Fuller, California Geological Survey*
*Photos: Chris Wills*

# Simplified Geologic Map of California
## with Geomorphic Provinces and GeoGems



**The geologic canvas.** The rock types ranging from modern to billions of years old provide the substance of the soil that has formed from them.

# 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 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.

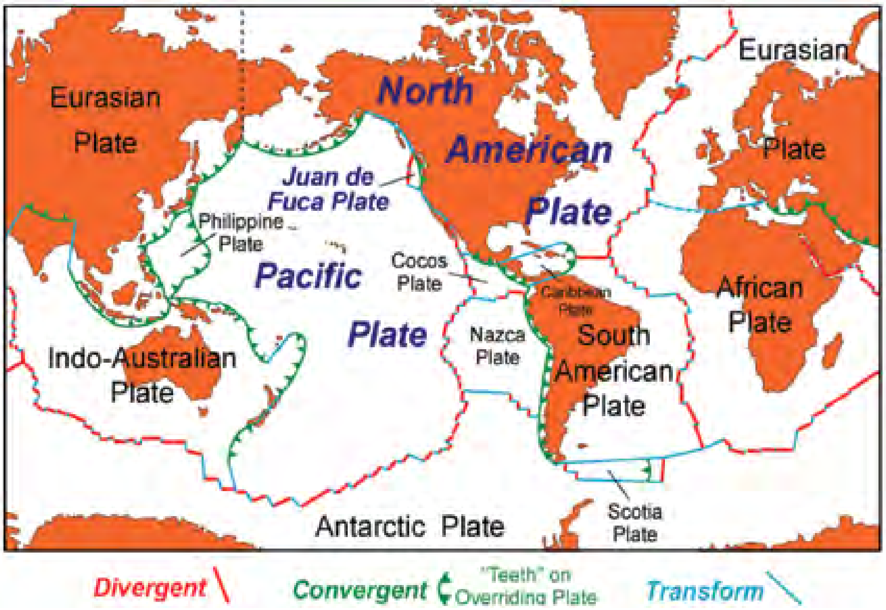
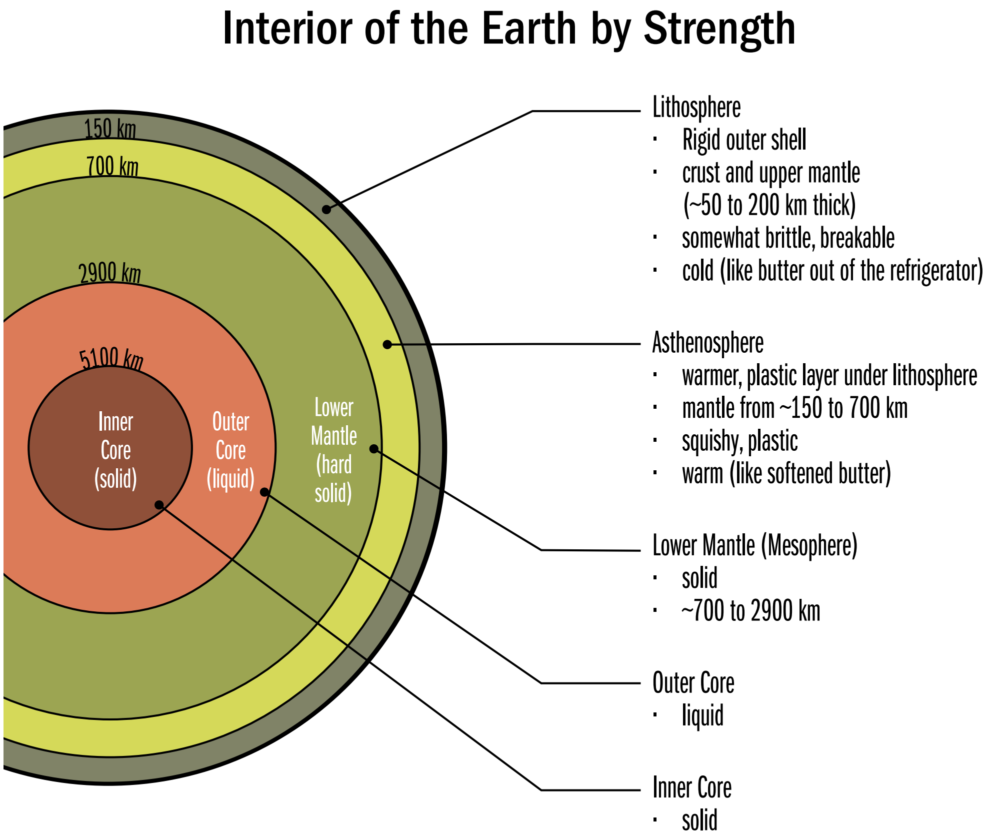


**Figure 2-2:** Tectonic plates and boundary types (Lillie, 2005).

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



Parks and Plates ©2005 Robert J. Lillie

**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 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.

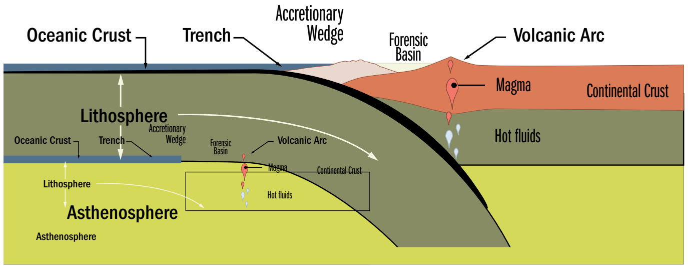


**Figure 2-4:** Subduction zone (Lillie, 2005).

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

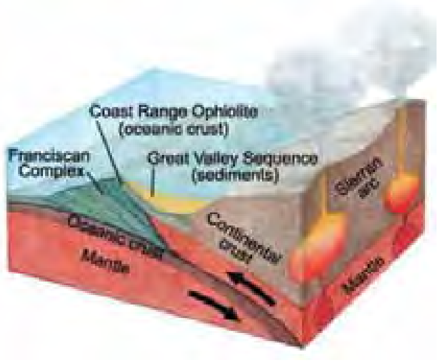


**Figure 2-5:** Subduction zone along California (Lillie, 2005)

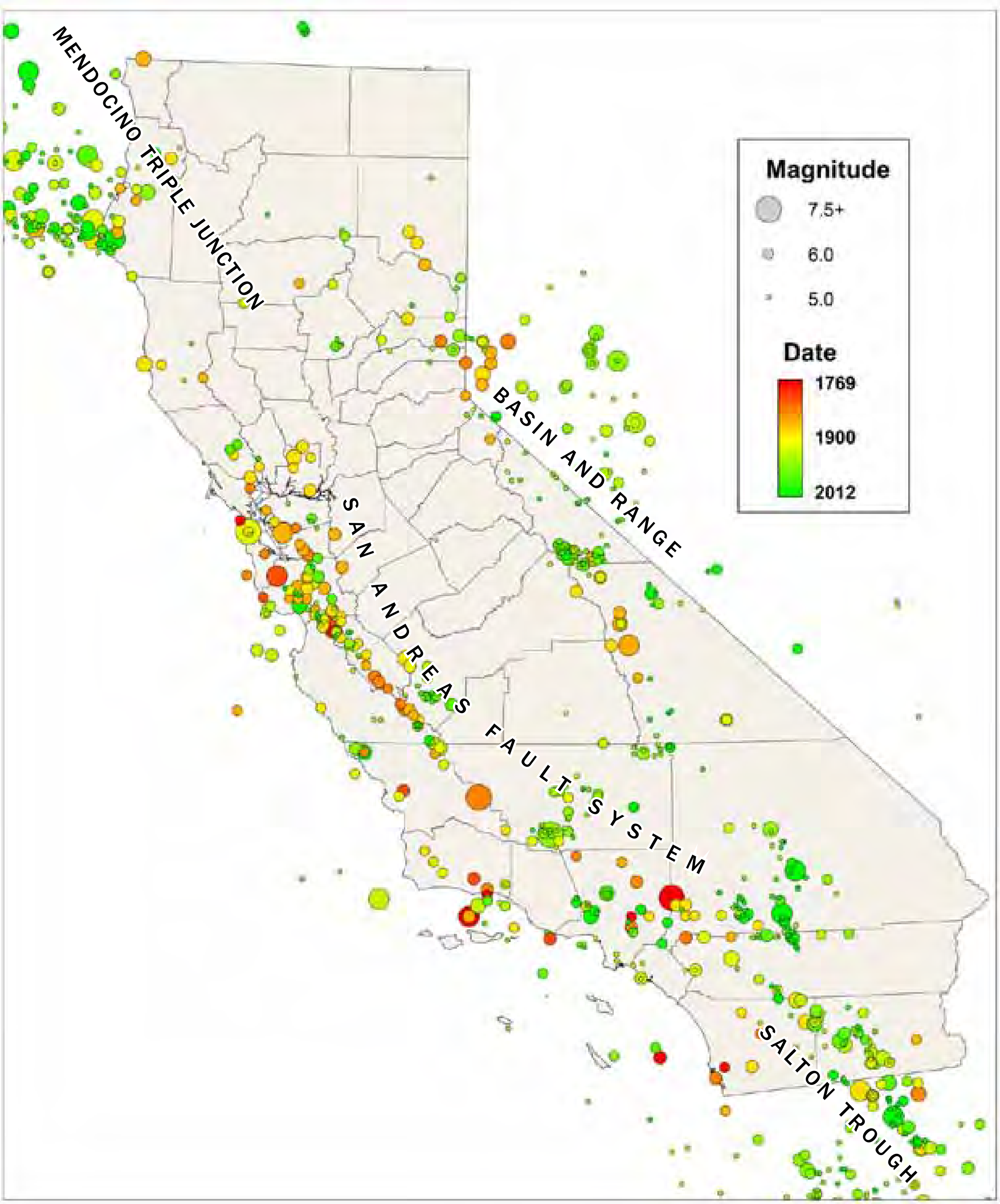


**Figure 2-6 Historic Earthquake Epicenters:** Clusters of earthquakes define the seismically active areas of California. Circles represent the locations of historic earthquakes. The size of the circle corresponds to the magnitude of the earthquake while the color indicates the general time period that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

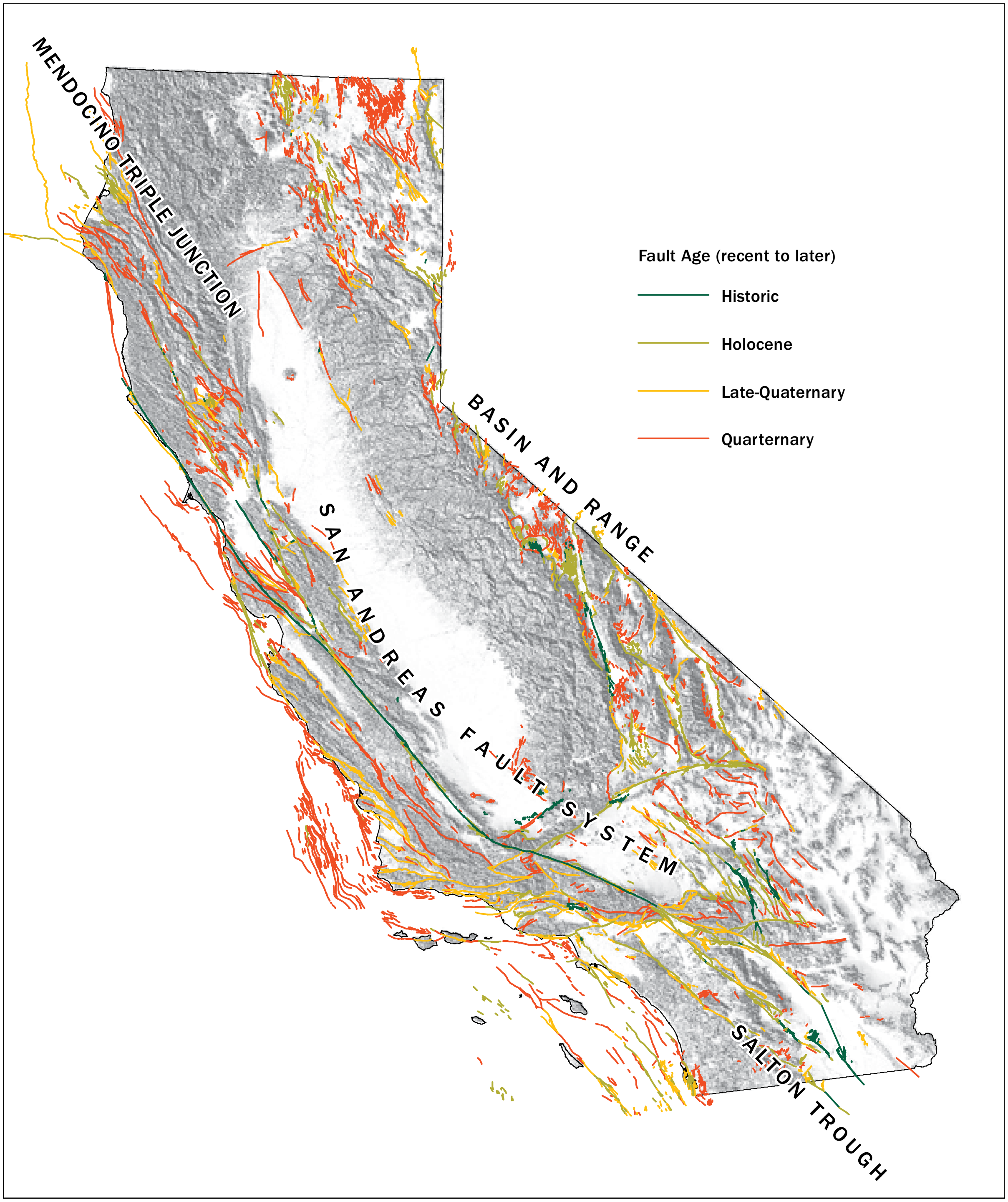


**Figure 2-7 Fault Activity Map:** Faults that experienced earthquakes either historically or during the Holocene are considered to be geologically active.

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.**

*Written by Mike Fuller, California Geological Survey*
*Photos: Mike Fuller*

Prepared by California Geological Survey, Department of Conservation | www.conservation.ca.gov/cgs
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# Coast Ranges Geomorphic Province

Photo: Jennifer Lotery

The **Coast Ranges** are a series of relatively low mountain ranges and associated valleys that trend northwest, subparallel to the active San Andreas Fault. Elevations of the ranges are typically 2,000 to 4,000 feet, sometimes reaching 6,000 feet above sea level. The Coast Ranges are predominantly composed of thick late Mesozoic and Cenozoic (251 million years ago to present) sedimentary rocks. The northern and southern portions of the province are separated by a depression containing the San Francisco Bay.

In some areas of the Coast Ranges, the topography is dominated by irregular, knobby outcrops of the landslide-prone rocks of the Franciscan Complex. In the Sonoma and Clear Lake regions Pliocene and younger volcanic flows, ash deposits, and cones are prominent. In the southern Coast Ranges, granitic and metamorphic rocks of the Salinian block lie to the west of the San Andreas Fault and extend from the southern extremity of the Coast Ranges, north to the Farallon Islands.

## Tectonic Setting

The Coast Ranges record both an ancient period of subduction and a subsequent regime of sideways deformation that persists today.

The rocks of the Coast Ranges (referred to as the Franciscan Complex) formed as a massive pile of rock and sediment in an ancient subduction zone. The bulk of the formation is a sheared matrix with large blocks of various rock types (mélange). Adjacent enclosed blocks exhibit distinctively different metamorphic histories. Pieces of the former subducting oceanic plate, known as the Coast Range ophiolite, are scattered throughout the province.

The San Andreas Fault system, consisting of numerous splays, runs almost the entire length of the Coast Ranges. To some degree, the San Andreas Fault system has shaped the landscape across the whole province south of the Mendocino triple junction. The movement along the faults for the past 20 million years has been generally strike-slip. The landscape reflects this sideways deformation with local areas of uplift or subsidence often reflected as parallel sequences of linear valleys and ridges.

## GeoGems

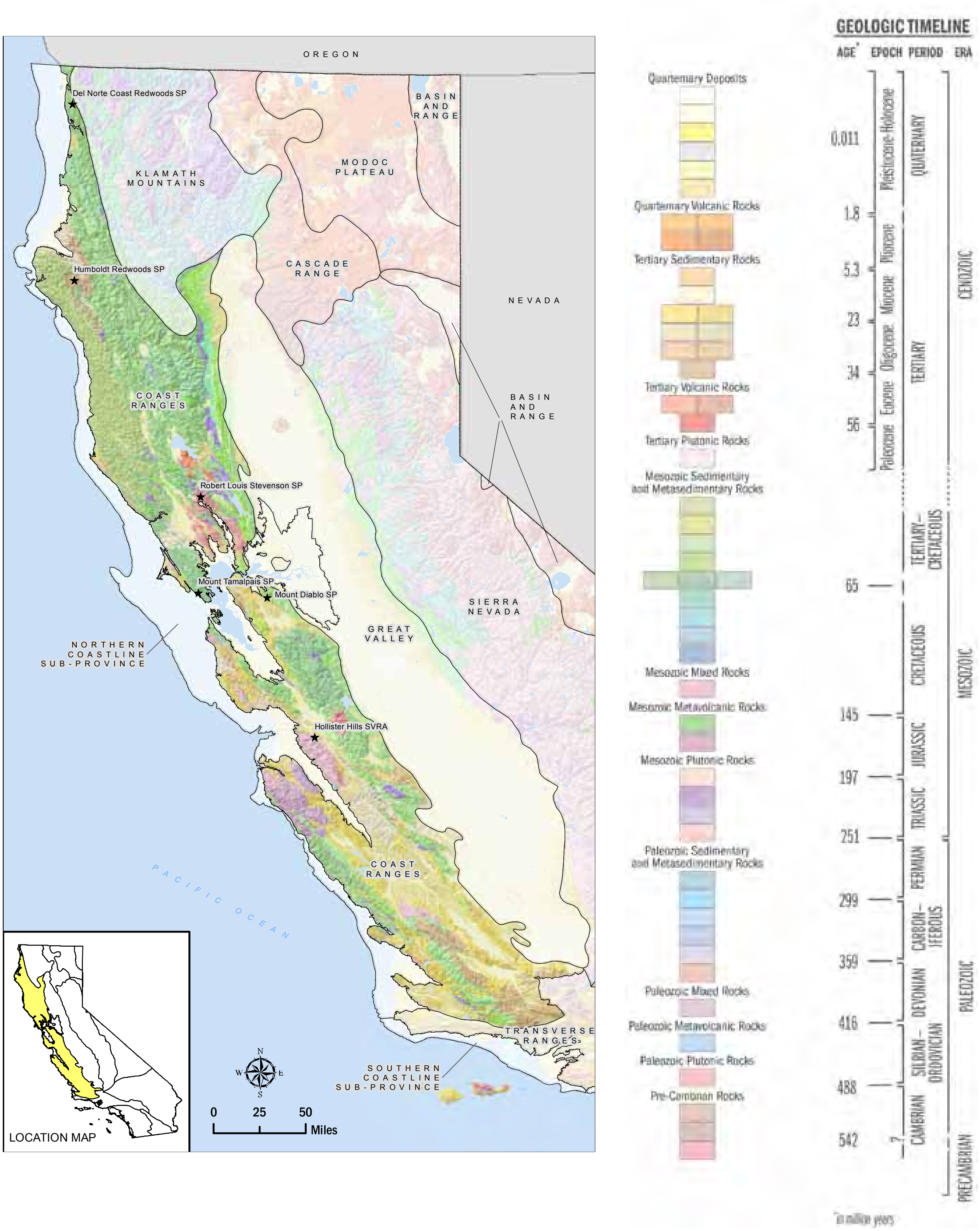
**Del Norte Coast Redwoods State Park** lies in the northernmost portion of the California Coast Ranges inland of the Cascadia Subduction zone where the North American plate plows over the descending Juan de Fuca plate. **Humboldt Redwoods State Park** represents the earthquake-prone region of the Mendocino triple junction where the Cascadia Subduction zone meets with the northern extent of the San Andreas Fault zone.

**Mount Tamalpais State Park** and **Mount Diablo State Park** are localized uplifts associated with the San Andreas Fault system. Inland, the San Andreas Fault figures prominently at **Hollister Hills State Vehicular Recreation Area. Robert Louis Stevenson State Park** illustrates volcanic activity associated with the growth of the San Andreas Fault.

Along the coastline, this sideways deformation is featured at **Salt Point State Park, Fort Ross State Historic Park,** and **Sinkyone Wilderness State Park.**

*Written by Mike Fuller and others, California Geological Survey*

## Simplified Geologic Map | Coast Ranges Geomorphic Province



**NOTES:**

**Prepared by California Geological Survey, Department of Conservation | www.conservation.ca.gov/cgs**
**for California State Parks | www.parks.ca.gov**

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# Del Norte Coast Redwoods State Park

Photo: CalTrans Staff

## Geologic Goulash

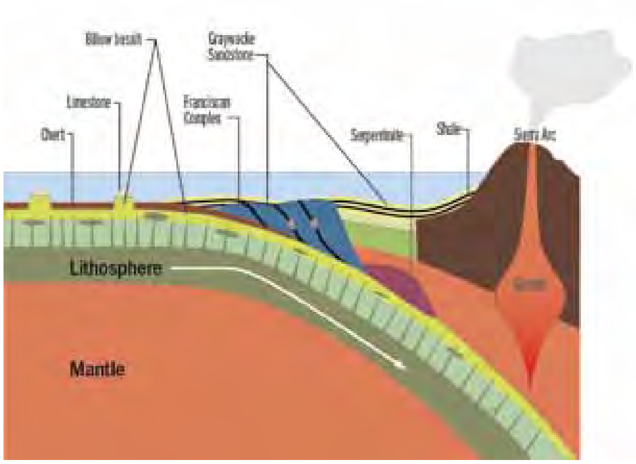
The cliffs tell a story of inexorable natural forces that only recently have been understood in light of plate tectonic theory. The rocks revealed in the sea cliffs are from the Franciscan Complex—the dominant geologic material underlying the entire Coast Ranges geomorphic province. The Franciscan Complex is made up of an accumulation of over 40,000 vertical feet (almost eight miles) of sandstone, shale, serpentine, chert, and greenstone (metamorphosed submarine volcanic rocks). The complex originated as oceanic floor and the accumulated sediments on top of it which have been scraped, bent, subducted and mashed against the North American continent.

**Feature/Process:**

Coastal geomorphology overprints on an exhumed accretionary complex

**What you can see:** Sea stacks, eroded remnants from the Franciscan mélange geologic unit. The mélange is the result of a tectonic plate collision that has been ongoing for at least the last 20 million years.

The rocks of the Franciscan Complex have been uplifted with the edge of the North American plate as subduction of the Gorda plate continues beneath it. The compression and uplift from this tectonic collision of oceanic and continental plates have produced an area of rugged topography along the north coast. In Del Norte Coast Redwoods State Park, the Franciscan Complex is represented by two similar units referred to as “broken formation” and “mélange.” Both are intensely sheared and fractured sandstone, siltstone and shale. “Broken formation” is a fractured assortment composed mainly of gray, thickly bedded sandstone with siltstone and shale interbeds. Mélange is highly sheared, dark gray siltstone and shale with isolated blocks of more intact material. Within the mélange unit, some blocks of different kinds of rock are large enough to be mapped separately. These blocks may be graywacke, greenstone, chert or



**Franciscan Complex:** The geologic formation that composes much of the Coast Ranges. It formed as a pile of rock and sediments that were scraped off a subducting plate to accumulate along the edge of the continent. It consists of numerous rock types encased in a highly convoluted matrix. Adapted from Bob Lillie, 2005.

**Why it's important:** The rugged cliffs of Del Norte Coast Redwoods State Park are composed of some of the most tortured, twisted, and mobile rocks of the North American continent. The rocks are mostly buried beneath soils and covered by vigorous redwood forests, which thrive in a climate famous for summer fog and powerful winter storms. The rocks only reveal themselves in steep stream banks, along road and trail cut banks, along the precipitous coastal cliffs and offshore in the form of towering rock monuments or sea stacks.

serpentine. The contrast in strength between the hard, relatively unfractured blocks and a weak sheared shale leads to rapid erosion of the matrix. The mélange near False Klamath Cove apparently had a number of large blocks, which now stand as offshore rocks and sea stacks along the coast and just offshore.

## Erosion and Landslides

Uplift of such weak rocks as the Franciscan Complex mélange leads to an unstable and active landscape. Winter storm waves beat on the base of the cliffs, removing the weaker shale and undercutting the slopes above. Erosion and landslides on the ocean-facing slopes are so frequent that soil cannot be retained, and vegetation cannot gain a foothold. Large landslides, some over a hundred feet thick, underlie many of the slopes and gradually move large blocks of rock down to the ocean waves. Weak rocks and sheared materials of the Franciscan mélange produce earthflow landslides in the vicinity of Wilson Creek; farther north, the rock is not as weak and the land slides as intact blocks.

## Final Thoughts

Precarious State Highway 101 has to accommodate the repeated shrugs of the landscape, as periodic landslides either deposit rocks and debris on the road, or take the entire roadbed for a ride down on massive, deep-seated landslides. The highway has been relocated inland more than once in response to the unstable terrain. This rugged and active nature has produced a dramatic meeting of land and sea—with relatively few and minor human intrusions rapidly erased by the ever changing terrain.

*Written by Chris Wills, California Geological Survey*
*Photos: Don Braun (except where noted)*

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# Humboldt Redwoods State Park

Photo: Bret Koehler

## Landscape Formation

Humboldt Redwoods State Park is located in a tectonically dynamic environment at the junction of three crustal plates known as the Mendocino Triple Junction. The redwood forests evolved along with the climate and landscape as the Coast Ranges and river valleys formed—driven by plate tectonics.

**Features/Process:**

Regional uplift-related geomorphology and jade pebbles

The regional compression has uplifted the Coast Ranges, blocking the prevailing Pacific storms so the Coast Ranges capture abundant rainfall. As the area is uplifted, the erosion power of the streams is increased. The streams incise into the rising ground creating deeper and steeper canyons. This creates an inner gorge.

## Inner Gorges

The walls of gorges are very unstable and numerous landslides and debris-slide slopes form along the streams. Periodically, the streams erode away the base of slides only to trigger additional slides in a never-ending process of landscape evolution.

Photo: Shannon Utley

**What you can see:** Steep, unstable hill slopes, active landslides, sediment-charged stream channels, and rare encounters with jade as pebbles and cobbles within gravel bars of the Eel River. The effects of continuous landscape change on new and ancient redwoods are on display.

## Landslides

The uplift of the Coast Ranges that has created the climatic conditions for the redwoods to survive has also created unstable hillslopes that can occasionally jeopardize some of the ancient trees. Due to abundant rainfall, which often occurs as severe, intense storms and proximity of the seismically active fault zones, landslides are commonly triggered by intense rainfall or earthquake shaking. Landslides that move as a mass of deep and relatively intact rock are common in the area, but the most common landslides occur in loose and unconsolidated earth materials on the slopes. The sloughing of weathered and loosened material is called debris sliding. If there is sufficient water in the material, the slide may degenerate into a liquid mass that can flow for long distances downslope as a debris flow. Some slopes in the northern Coast Ranges are sculpted by repeated debris-slides and debris flows, creating a landform called a debris slide slope.

## Stream Conditions

Input of some landslide-carried debris and sediment to streams is beneficial for aquatic and terrestrial habitat, for instance by providing 1) rocks and logs for pool formation and gravel for spawning beds and renewing floodplains, like the one

Photo: Bret Koehler

**Why it's important:** Humboldt Redwoods State Park has international reknown and is classified as both a World Heritage Site and an International Biosphere Reserve. The coast redwoods (sequoia sempervirens) exist only in a narrow band that runs for 500 miles from Monterey to just over the Oregon border. Needing a warm, moist, and foggy environment, coast redwoods are confined to the coast and elevations below 3,000 feet. Redwoods are "living fossils" dating back 100 million years to the Cretaceous Period—the time of the dinosaurs. The oldest redwoods range from several hundred to as much as 2,000 years old. Old growth groves are truly monuments of the past. Prior to the Ice Ages (1.8 million years ago), the redwood forests were much more widespread but became restricted to their present range due to cooler temperatures and regional uplift of the Coast Ranges.

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occupied by the Rockefeller Forest, and 2) nutrients and sediment necessary for forest function. Excessive landslide debris though can adversely impact aquatic habitat by filling pools and silting in gravel beds. In the historical period following European settlement, land use practices, such as, timber harvesting and road building have accelerated erosion by altering natural drainage patterns, soil and water conditions, and decreasing root reinforcement of soils on steep slopes.

**… a certain amount of landslide carried debris and sediment to streams is necessary for aquatic and terrestrial habitat …**

## Origin of Jade

The region surrounding the park and areas upstream along the South Fork of the Eel River are underlain by rocks from the Franciscan Complex—the dominant geologic material underlying the entire Coast Ranges geomorphic province. The Franciscan Complex is made up of an accumulation of over 40,000 vertical feet (almost eight miles) of sandstone, shale, serpentine, chert, and greenstone (cooked and squeezed submarine volcanic rocks). The complex originated as oceanic floor and the accumulated sediments on top of it have been scraped, bent, subducted and mashed against the North American continent.

As subduction forces oceanic plates beneath the continent, some material from great depths within the earth gets squeezed up to the surface. Very dense minerals within these deep earth rocks are intensely sheared in the process. During their journey to the surface, the minerals formed at great pressures and temperatures changed to minerals that are more stable in near surface pressure and temperature conditions, such as serpentine, jadeite and nephrite jade.

*Photo: Mike Fuller*

Outcrops of serpentinite within the park along the South Fork of the Eel River may be the source of jade pebbles and cobbles found on gravel bars. Other potential source areas may lie upstream of the park.

## Final Thoughts

This landscape continues to evolve by the dueling processes of uplift against erosion.

*Written by Gerald Marshall, California Geological Survey*

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# Robert Louis Stevenson State Park

Robert Louis Stevenson State Park is situated along the crest of the Mayacama Mountains, within the northern California Coast Ranges geomorphic province. The park is on the slopes of Mount St. Helena, a majestic double-peaked mountain that rises above the Napa Valley to an elevation of 4,339 feet.

## Sonoma Volcanics

**Features:**

Volcanic geomorphology and remnant silver ore

The Sonoma Volcanics include a wide spectrum of volcanic rock types, from silica-rich rhyolite, to dacite, andesite and basalt. The rocks all began as molten material (magma) in a chamber deep beneath the earth's surface. Accumulation of gas and high pressures in the magma chamber forced magma to the surface as lava flows, or blasted out in an aerosol of molten material. Molten material cast skyward in violent eruptions quickly solidifies to form ash and larger globular masses known as volcanic bombs. After this material falls to earth, it may be transported by gravity or water, mixed with other volcanic debris, and then eventually accumulate and harden to form pyroclastic rocks.

### What you can see:

On the southeastern flank of the mountain is the historic Silverado silver mine and the remains of the mining camp that flourished briefly during the 1870s. Southward from the peak along the range crest are Table Rock and the Palisades—a stunning wall of craggy volcanic cliffs that extends for more than a mile along the ridge that overlooks the town of Calistoga.

Like Mount St. Helena, the Palisades is composed of pyroclastic rocks. The principal cliff-forming deposits consist of a thick andesitic agglomerate layer over rhyolitic ash-flow tuffs. Below the cliffs are outcrops of mega-breccia, composed of great blocks of jumbled volcanic rock.

Pyroclastic rocks in the park include tuff—composed of fine volcanic ash; welded tuff—formed when some ash fragments, still slightly hot and plastic, were combined and compressed; agglomerate—composed of a mix of ash, volcanic bombs, and other fragments; and volcanic breccia—composed of mixed sizes of angular rock fragments, in a matrix of finer pyroclastic material.

## Mount St. Helena—Not a Volcano, But a Resurgent Caldera!

Mount St. Helena could be mistaken for a volcano, but any resemblance to an actual volcanic edifice is coincidental. The mountain is composed of more than 4,000 feet of interlayered tuff, volcanic breccia and, towards the summit, welded rhyolitic tuff. This massive stack of material is thought to have accumulated within a caldera collapse structure. A caldera is a large depression that forms when a volcano collapses into the cavity once occupied by erupted magma. After collapse of the Mount St. Helena caldera, intrusion and movement of additional magma below the caldera is interpreted to have resulted in resurgent eruptions and uplift of the central collapsed area. This resurgent uplift, combined with more recent tectonic uplift, block faulting, and progressive erosion, produced the topographic high we see today.

**Why it's important:** Unlike most of the northern California Coast Ranges, the Mayacama Mountains are largely volcanic in origin. The rocks that form Mount St. Helena and the Palisades are part of a group of rocks known as the Sonoma Volcanics. The Sonoma Volcanics erupted from a number of different volcanic centers in the Napa-Sonoma region between 2.6 and 8 million years ago. In addition to providing dramatic scenery, the rich soils developed from the volcanic rocks support and nourish the region's agricultural crown jewels—premium quality wine grapes.

The last episodes of volcanism led to the formation of silver and gold deposits. These precious ore veins attracted an early flood of fortune-seekers to the region.

## Silver Mining

After the miners made quick work of the easy pickings and moved on, a derelict bunkhouse at the Silverado mine served for several months in 1880 as the honeymoon suite for the now-famous (but then broke) writer Robert Louis Stevenson and his new wife, Fanny Vandegrift Osbourne. Stevenson's book, The Silverado Squatters, described their stay at the camp.

The historic Silverado mine site is one of several precious metal mines in the Calistoga mining district. The mine extracted silver and some gold from thick veins of milky quartz and zones of mineralization along the margins of the volcanic chamber. The mineralization developed when the hydrothermal (hot-spring) fluids migrated through fractures in the volcanic and older wall rocks. Ore fluids are thought to have been heated by magma introduced during the late resurgent phase of volcanic activity beneath the Mount St. Helena caldera. The Silverado mine opened in 1872, and for a brief period drew upward of 1,500 people to a bustling mining camp that included several saloons and a hotel. Two main tunnels were constructed into the mountain, with a connecting vertical shaft located farther up the mountain. The miners followed the ore veins to a depth of almost 600 feet, and curtailed the mining pursuits since the cost to extract the ore exceeded the value of the target precious metals. When Robert Louis Stevenson came to the area in 1880, the mine had already been abandoned.

## Final Thoughts

Often feared, volcanic eruptions deliver from the depths essential minerals on which society depends.

*Written by Marc Delattre, California Geological Survey*
*Photos: Mike Fuller*

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# Mount Tamalpais State Park

## Franciscan Mélange

The term terrane (different from terrain) refers to a large, fault-bounded "packet" of rocks having a geologic makeup and history distinctly different from surrounding areas. Several different terranes have been recognized in the Mt. Tamalpais area, but most of the park is underlain by mélange. The Franciscan mélange (French for "mixture") is composed largely of shale and sandstone that has been crushed and ground to the consistency of soil. Enclosed within the soil-like matrix are isolated blocks of hard rock from different terranes that vary from smaller than a soda can to larger than a house. This composition of hard blocks within an easily eroded matrix produces distinctive landscapes unique to the mélange. The presence of mélange on the fog-shrouded hillsides of Mount Tamalpais State Park leads to ghostly settings, where lonely rocky knobs protrude from grassy slopes like monuments in an ancient graveyard.

### Features/Process:

Geology of a tectonic mélange with red cherts and blue schist

**What you can see:**
Mount Tamalpais is part of the California Coast Ranges geomorphic province, a region of fascinating geology produced by the interaction of slowly moving tectonic plates (giant pieces of the earth's crust) over millions of years. Visitors may encounter a "suite" of rock types at the park.

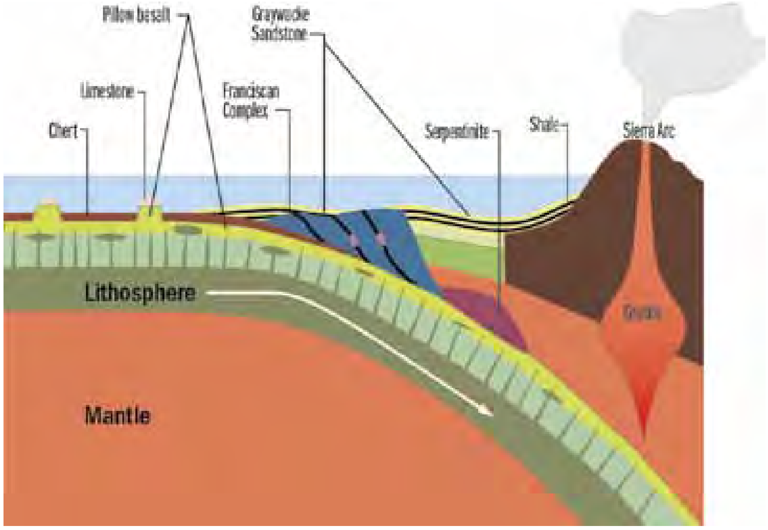
## Radiolarian Chert

Chert has played a particularly important part in deciphering the age and origins of the Franciscan Complex because it is one of the few rock types in the rock unit where fossils have been preserved. Chert is created from the silica skeletons of billions of tiny plankton called radiolaria, which accumulate on the seafloor. Radiolarian skeletons come in a myriad of shapes that scientists have been able to categorize by age and ocean environment. Studies of radiolaria found in chert from the Marin Headlands, south of the park, and blocks in the mélange suggest that the chert was deposited between 200 and 100 million years ago (Early Jurassic to Late Cretaceous time), and in tropical to subtropical environments far to the south of their current location.

Most Franciscan chert has a red color produced by minute amounts of oxidized iron in the rock. However, green, black, and gray varieties are also common, reflecting different minerals and oxygen levels present when the rocks formed. The resistant chert beds are frequently separated by paper thin layers of soft shale creating thinly bedded sequences referred to as ribbon chert. Red ribbon chert forms some of the more interesting rock outcroppings in the mélange at the park, including those where the bedding has been folded and contorted into stunning designs.

### Why it's important:

The Franciscan Complex has perplexed geologists from around the world, and has served as an important proving ground for modern plate tectonic theories. It provides an excellent above-ground laboratory of what happens in subduction zones beneath the oceanic crust and continental crust.



*Adopted from Bob Lillie, 2005.*

The story that geologists have derived from the rocks begins roughly 200 million years ago, with creation of new oceanic crust (seafloor) from volcanic eruptions of basalt along a mid-ocean rift (spreading center) in the Pacific. Once new seafloor formed and moved away from the rift, sediments slowly blanketed the basalt. Chert was deposited in the open ocean, and then layers of sand and mud (graywacke and shale) were added as the seafloor plate moved from the spreading center (rift). When the dense oceanic crust collided with the thick continental North American plate, it was forced under the crust, down into the hot plastic mantle along a subduction zone. Basalt and sedimentary rocks scraped from the surface of the subducting oceanic crust were churned in with continental fragments and sediments caught up in the chaos of the subduction zone. Portions of this mixture were pushed out of the subduction zone to be accreted (attached) to the North American plate in a succession of tectonic terranes that collectively form the Franciscan Complex.

## Large Landslides

The dynamic geologic environment that helped build the beauty of Mount Tamalpais has also endowed the area with ongoing hazards from landslides and earthquakes. Rocks weakened by tectonic shearing, combined with the mountainous terrain and soakings by storms from the Pacific, provide ideal conditions for unstable slopes. This is particularly true along the coast where vigorous, relentless ocean waves constantly cut away at the base of the hills. Highway One crosses many enormous landslides some thousands of feet wide. Most of these are ancient features that may remain dormant and unnoticed over long periods. However, events such as earthquakes or unusually wet winters can sometimes reactivate movement over all or parts of the old landslides. Sliding can occur as slow creep that rumples and deflects roadway pavement, or as abrupt failures with more severe consequences. A dramatic example of this occurred within the park, south of Lone Tree Creek in 1990, when movement of a known landslide progressed from inches per month to feet per month between January and May. This deep-seated landslide dropped some 600 feet of roadway and closed the highway for nearly two years.

## Transition from Subduction to Transform Boundary

The process of subduction and accretion that created the Franciscan Complex continued in the Mount Tamalpais area up until about 27 million years ago, when plate movements and conditions along the continental margin underwent a huge change. Instead of colliding, the Pacific and North American plates began to move past each other, the Pacific Plate moving north along what would become the now-famous San Andreas Fault.

## Final Thoughts

The spectacular vistas, unique landforms, and geologic hazards of Mount Tamalpais all reflect the amazing tectonic events of the past, as well as the ongoing plate motions that continue to reshape the California Coast Ranges.

*Written by Marc Delattre, California Geological Survey*
*Photos: Mike Fuller*

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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 8

# Mount Diablo State Park

## Ancient Seafloor

**Features:**

Tectonic geomorphology of an ophiolite and surrounding sediments and fossils

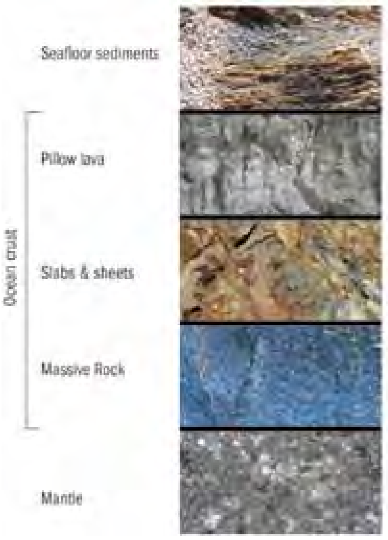
From a distance Mount Diablo may resemble a volcano, but the mountain's origin is very different, although arguably just as exciting. Much of the core of Mount Diablo is made up of a special rock sequence/assemblage called an ophiolite. Ophiolites originate at the spreading centers of oceans and where oceanic plates collide with continental plates. On Mount Diablo, the ophiolite is dismembered.

During ophiolite formation, molten rock from below the oceanic crust penetrates into seafloor fractures and either slowly cools and solidifies as sheets of diabase or erupts onto the seafloor and quickly cools to form pillow basalts (as found on Mitchell Peak). Basalt and diabase are chemically the same but differ in texture due to their different rates of cooling. Outcrops of pillow basalts have rounded shapes reminiscent of randomly stacked pillows.

Serpentinite, California's official state rock, originates deep in the mantle where the surrounding materials are very hot and semi-plastic. It typically finds its way to the earth's crust and surface by following paths of weakness and faults. Serpentinite crops out on the mountain as a narrow band of rocks northwest of the summit. Intermixed within the serpentinite are related rocks rarely found on the earth's surface: harzburgite and pyroxenite. These coarse-grained rocks came from a layer deep below the oceanic crust called the mantle.

Near Mount Diablo's summit, rocks of the Franciscan Complex (also formed during the subduction process) crop out. Included are fragments of basalt, shale, sandstone, and occasional blocks of blue-colored metamorphic rocks called blueschist. Also included are reddish beds of chert which are made of the skeletal remains of small sea creatures called radiolaria.

In contrast to an ophiolite, the Franciscan Complex is a chaotic mix of rocks scraped off the Farallon plate and plastered onto the edge of the North American plate as the two plates collided hundreds of millions of years ago. On land, the Franciscan Complex consists of large and small blocks of various rock types encased in a sheared matrix.



**Ophiolite:** A layered assemblage of rocks that formed as a section of oceanic crust. The crust forms at rifts in the oceanic crust such that a characteristic sequence of layers is formed. The rate of cooling of molten rock is controlled by the depth below the ocean floor where water quenches the rock. The deeper layers are cooled more slowly while the uppermost layers cool rapidly. Pillow basalts typify the upper layers while intermediate layers develop as vertical slabs and lowermost layers develop as massive rock.

## Emergence of Land

Younger rocks surround the core of the mountain and provide evidence that subduction along the plate margin ended and the region was uplifted out of the sea during the Tertiary Period (2.6 to 65.5 million years ago). Layers of progressively younger rocks are found away from the mountain and in the surrounding valleys.

The “wind caves” found on the mountain are formed in Domengine Sandstone (deposited about 50 million years ago). These caves were not formed by wind, but were created by water that seeped through fractures and dissolved portions of the rock, eroding out the caves in the softened rock. Mineral concretions are also found in the sandstone, as resistant round cannonball shapes, formed by mineral deposits that armor the sandstone against erosion.

**What you can see:** Lofty Mount Diablo is a chunk of ancient sea floor that has been shoved up to form the most prominent mountain in the East Bay. It retains fragments of oceanic crust, underwater lava flows, a rich collection of marine and terrestrial fossils, folded and faulted rock outcrops, and caves that illustrate its transition from seafloor to the complex mountain of today.

**Why it's important:** Mount Diablo is a dominant topographic feature in northern California. It was established in 1851 as the initial point of the Mount Diablo Base Line and Meridian for land surveys spanning two-thirds of California and all of Nevada. The mountain's summit boasts spectacular panoramic views. Less well-known is the complicated geologic history that produced this intriguing landscape.

Current plate tectonic theory places the origin of the mountain thousands of miles southwest of its current location. The oceanic fragment was crammed and squeezed with other rocks for millions of years along the interface of the Pacific and North American plates. Mount Diablo provides excellent examples of the types of rocks and geologic processes that occur along a continually evolving plate margin.

## Fossils

In addition to the microscopic radiolaria associated with the Franciscan chert near Mount Diablo's summit, some of the younger rocks are rich in fossils. The Briones Sandstone of Miocene age (23 my – 5 my) is particularly rich in shell fossils. The Pleistocene (less than 1.8 my) Green Valley Formation represents the final emergence of the area from the sea and includes fossils of mammals such as mastodons, camels, and saber-toothed cats.

## Growth of a Mountain

Mount Diablo as an edifice is geologically young and only began to form about two million years ago during the Pliocene. Regional uplift has produced the steeply dipping beds that surround the mountain. Tilted beds that are more resistant to erosion tend to form distinctive hogbacks, which are sharp crested ridges that stand out in contrast to the adjacent more easily erodible beds.

Deformation continues today as the mountain is squeezed between the active Greenville and Concord faults. The growth of the mountain occurs episodically during large earthquakes along a buried fault under the mountain know as the Mount Diablo thrust fault. The fault has not moved historically, but scientists estimate that there is a 1% chance that it will produce a large earthquake in the next 30 years. Such earthquakes represent the continuing tectonic forces that have created, and will continue to shape Mount Diablo.

## Final Thoughts

When this landmark became the basis of our survey system in 1851, we considered it dormant; we now know the mountain is still growing.

*Written by Tim Dawson, California Geological Survey*
*Photos: Mike Fuller*

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# Hollister Hills SVRA

State Vehicular Recreation Area

## Two Worlds Collide

The earth's crust is composed of tectonic plates that slowly slide over the earth's viscous, fluid mantle. These plates, composed of either oceanic crust or continental crust, meet in different ways. They may mash together, such as where the Indian plate has pushed into the Eurasian plate, creating the Himalayas. Or an oceanic plate may slip underneath another plate, creating a subduction-related volcanic arc. The Cascade Range is a volcanic arc, which stretches from northern California through Oregon and Washington and into British Columbia, and includes Mount St. Helens, among other active volcanoes. Or the plates may slide past each other along what is called a transform margin, such as along California's San Andreas Fault. South of the town of Hollister and due east of the Monterey Bay, within the hills and peaks of the Gabilan Range, the Hollister Hills State Vehicular Recreation Area (Hollister Hills) straddles a portion of the San Andreas.

**Process:** Active faulting

**What you can see:**
linear valleys, shutter ridges, offset channels, soil and topographic contrasts

## San Andreas Fault

The San Andreas Fault is a transform margin between the Pacific oceanic plate and the North American continental plate. The San Andreas Fault extends over hundreds of miles from the Gulf of California to Shelter Cove near Cape Mendocino. Geomorphic features indicative of active strike-slip (lateral) movement along the fault zone include elongate hills known as pressure ridges or, where they block drainages, shutter ridges. Offset drainages are another common fault-generated feature at the park.

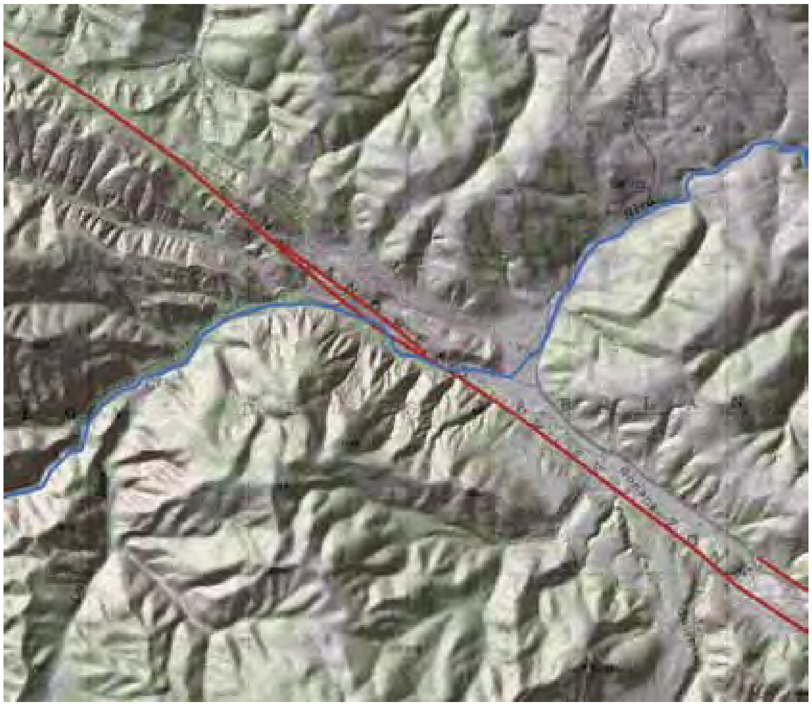
Movement along this fault is, of course, exhibited by earthquakes, from small shakers to devastating events, such as the famed 1906 San Francisco quake. There are also portions of the fault where the plates quietly slide, or creep, past each other. This occurs on that portion of the San Andreas Fault which runs through Hollister Hills.

Fault creep sounds relatively innocuous. Indeed, fault creep instruments installed at Hollister Hills have recorded movement of about one half inch for every year. But fault creep is relentless, and movement on the San Andreas Fault began millions of years ago. The resultant effect of the strike-slip movement, in the Hollister Hills landscape is dramatic.

For instance, the northwest-southeast trace of the San Andreas Fault is delineated by the shallow, linear valley that stretches between the Lower Ranch and Upper Ranch areas of Hollister Hills.

Linear hillocks within the valley, such as Radio Ridge in the Lower Ranch and the hills between Cienega Road and the grand prix track in the Upper Ranch, are aligned along a northwest path and are called shutter ridges, created by the slow seismic smearing

**Why it's important:** The landforms and underlying geology found at Hollister Hills embody a dynamic history of shifting tectonic plates—giant fragments of the earth's crust. The park is situated at the active continental margin, where the Pacific plate and the North American plate are moving slowly past each other along the San Andreas Fault. East of the fault, rocks of the Franciscan Complex form the core of the central California Coast Ranges. To the west, rocks of the Salinian terrane represent a displaced block of the earth's crust that has been dragged northward along the fault over millions of years.



The red line shows the San Andreas Fault which has offset the course of Bird Creek, the blue line. The creek flows from left to right

An excellent example is Bird Creek, which flows northeast from the southern corner of the Lower Ranch. The creek is diverted more than 4,000 feet southwest along the fault trace before continuing northeast near the main entrance of Hollister Hills on Cienega Road.

between the plates. And drainages—both manmade and natural—that flow across the fault have been offset. A concrete canal at the DeRose Vineyards, just up Cienega Road, southeast from the Upper Ranch, displays more than three feet of right-lateral offset. The historic DeRose corking facility near the canal also straddles the fault and has been literally torn in two, due to the plate movement. It has been retrofitted to function as two separate structures.

There are two different landscapes at Hollister Hills. The topography is higher and steeper southwest of the San Andreas Fault trace, and the vegetation is relatively dense and varied. Northeast of the trace, the topography is muted, softer, the hills more rounded and the sparse vegetation consists mostly of oak woodland, scrub, and grasses. This is the result of the slow northwest progression of the Pacific plate relative to the North American plate along the San Andreas Fault.

The higher and steeper hills southwest of the fault trace are underlain by granitic rock and relatively minor amounts of metamorphic rock. Known as the Salinian terrane (named after the nearby town of Salinas), the granitic rock is at least 145 million years old and is likely the southern extension of the Sierran granitic intrusion—the rocks that comprise the spine of the Sierra Nevada. The rock beneath the rolling hills on the northeast side of the fault consists of much softer and younger siltstones and sandstones derived from sediments deposited in a near-shore environment. These rocks are approximately five to six million years old.

**The landforms and underlying geology found at Hollister Hills embody a dynamic history of shifting tectonic plates—giant fragments of the earth's crust.**

The soils that develop from the rock southwest of the fault trace are significantly different from the soils derived from the rock northeast of the fault. In the granitic terrain, the rock is hard but may be brittle and easily crumbled (friable) where exposed. Its light-colored soils are sandy and silty and drain well, but they mostly lack cohesion due to an absence of clay. These soils are more vulnerable to erosion, particularly from runoff concentrated in a ditch or gully.

The younger, softer sedimentary rock northeast of the San Andreas Fault crops out in few places because it quickly weathers to a dark brown to black, clay-rich soil.

The contrasts can be readily seen from the air. The soil and terrain either side of the fault provide different habitat for plants and animals.

## Final Thoughts

The geology of Hollister Hills presents a unique recreational choice to the off-highway vehicle enthusiast—whether to explore the Pacific plate, the North American plate, or both.

*Written by Will Harris, California Geological Survey*
*Photos: Stephen Reynolds*

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# Northern Coastline Geomorphic Sub-Province

Essentially, the coastline itself qualifies as a distinct geomorphic province evenly divided between north and south. Because the coastline is 1,100 miles long, the climate and water temperatures in the south are more mild than in the north. The flora and fauna vary accordingly. The California coastline is a dynamic boundary zone, of varying width, where geologic forces collide. Coastal landforms include beaches, dunes, tide pools, estuaries, lagoons, steep cliffs, marine terraces, and sea stacks.

The coastline can be subdivided into two sections. The northern section runs the length of the Coast Ranges province; the southern runs along the western edge of the provinces of the Transverse Ranges and the Peninsular Ranges. Along the northern section, the coastal geomorphology is superimposed on the landforms of the Coast Ranges province. The northern section runs north-by-northwest from Point Conception north to Oregon. Due to the orientation, the winter storms and waves tend to attack the northern shores head-on without the buffering effect of a broad continental shelf. Beaches are often cobbly or gravelly with scattered sandy beaches.

The position of the shoreline is directly related to sea level and land elevation, both of which are variable through time. Sea level was as much as 400 feet lower during the last Ice Age because so much water was trapped as ice on the glaciers that covered northern and southern latitudes. During this time the shoreline position was as much as several miles west (near the Farallon Islands) of its current location. During the Ice Ages, major rivers cut deep canyons into the continental shelf creating submarine canyons such as the Monterey submarine canyon (which is twice as deep as the Grand Canyon). During the last interglacial period, sea level was approximately 15 to 20 feet higher and coastal wetlands and estuaries were correspondingly much more extensive than today.

## Tectonic Setting

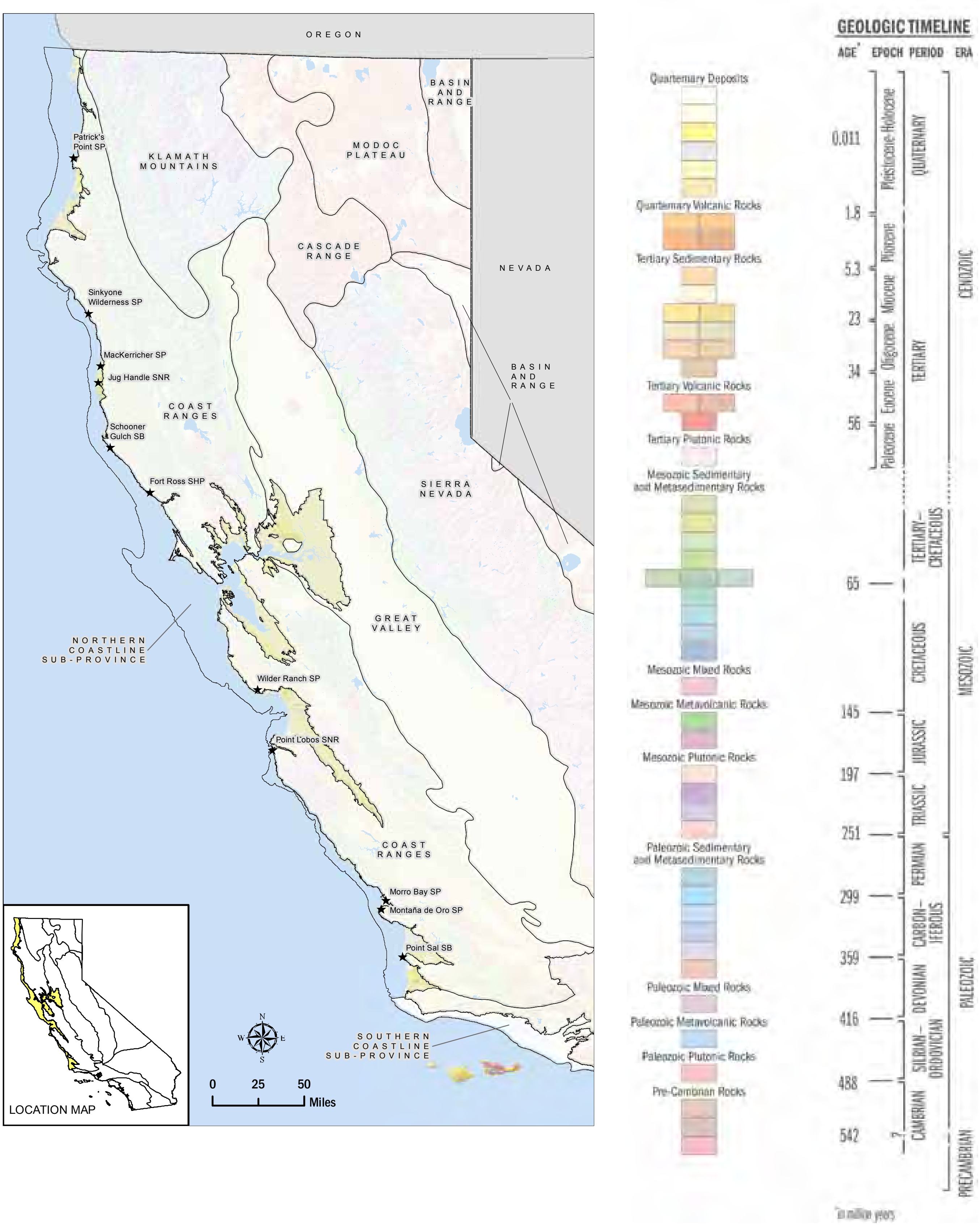
Portions of the coast have been uplifted due to tectonic forces, while others have subsided. The interplay of uplift and sea level fluctuations produced numerous marine terraces exhibited all along the coast. The highest terraces can extend several miles inland to what was once the shoreline, as in Mendocino County. Subsidence, along with sea level rise since the end of the last Ice Age, has drowned river mouths and flooded into the San Francisco Bay to create the largest estuary on the west coast. This moved the shoreline over 10 miles inland. Such a dynamic setting has produced a long list of landscapes and features including: accreted terranes, marine terraces, sea stacks, dunes, a fen, a pygmy forest, tafoni, concretions, and black sands.

## GeoGems

Eleven GeoGems represent the northern coast: **Patrick's Point State Park, Sinkyone Wilderness State Park, MacKerricher State Park, Jug Handle State Natural Reserve, Schooner Gulch State Beach, Salt Point, Fort Ross State Historic Park, Wilder Ranch State Park, Point Lobos State Natural Resource, Morro Bay State Park, Montaña del Oro State Park,** and **Point Sal State Beach.**

*Written by Mike Fuller, California Geological Survey*
*Photo: Jennifer Lotery*

# Simplified Geologic Map | Northern Coastline Geomorphic Sub-Province



**NOTES:**

**Prepared by California Geological Survey, Department of Conservation | www.conservation.ca.gov/cgs**
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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 11

# Patrick's Point State Park

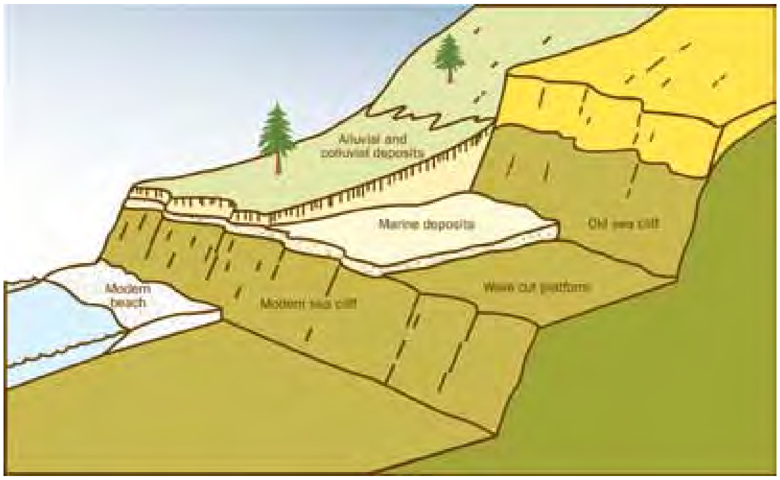
## Uplifted Terrace and Sea Stacks

Most of Patrick's Point State Park rests on an ancient marine terrace uplifted from the sea approximately 83,000 years ago. The terrace averages about 200 feet above the modern sea level and is covered with wave-deposited sand and gravel. Offshore the waves are carving a new bedrock platform, which will serve as the base for a new terrace.

**Features:**

Coastal geomorphology and agate pebbles

Resistant rock outcrops protruding above the ancient terrace (Ceremonial Rock, Lookout Rock, and Wedding Rock) are ancient sea stacks like the modern ones now visible offshore amidst the crashing surf. Regional uplift and global sea level changes have elevated Ceremonial Rock and Wedding Rock out of the surrounding ocean: Ceremonial Rock towers 107 feet over the marine terrace.



**Marine terraces** consist of a wave-cut bedrock platform (bench) with a thin, discontinuous blanket of marine and younger non-marine deposits. The origins of the terraces are tied to changes in climate and associated fluctuations in eustatic (worldwide) sea level during the Pleistocene epoch 11,000–1.1 million years ago. Modified from Weber and Allwardt, 2001.

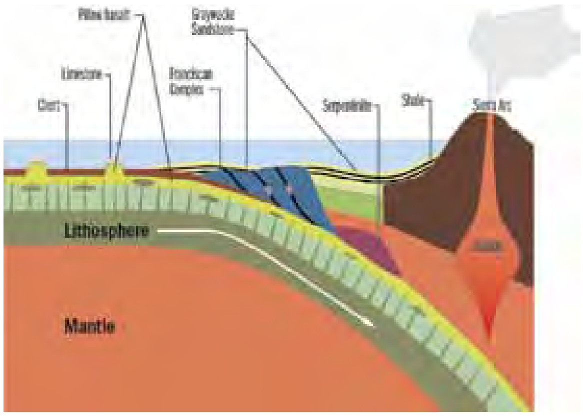
## Franciscan Complex

The Franciscan Complex, exposed along the base of the cliffs south of Agate Beach, is well-named because it is an extremely complicated mix of rocks that accreted to the western edge of the North American plate when the Pacific seafloor subducted beneath the continent. This collision produced a vast pile of rock material derived from both the deep ocean and the continental shelf, mixed and cooked by volcanic and tectonic activities to produce a goulash of mixed-origin rocks.

The floor of the Pacific Ocean was, and still is, being forced under North America as the two sections of earth's crust (plates) slowly collide with one another. As the Pacific plate descended below the North America plate, it dragged seafloor sediments and under-water landslide deposits along with it. The entire sediment/crust package was altered physically and chemically under the overriding plate as it was compressed and deformed under tremendous pressures, yet at relatively low temperatures.

The result is called a mélange (French for "mixture"). The fine-grained portion (matrix) of the mélange is generally shale-rich, heavily sheared, very weak, and easily eroded. Blocks within the mélange can vary in size from inches to many hundreds of feet across.

The block composition can vary widely because of the mixing action that occurred within the subduction zone. Relatively unaltered shale, and sandstone, chert, and limestone that were not buried deeply are easily recognized. But deeply buried, highly altered metamorphic blocks in the mélange bear little resemblance to their



**Franciscan Complex:** The geologic formation that composes much of the Coast Ranges. It formed as a pile of rock and sediments that were scraped off a subducting plate to accumulate along the edge of the continent. It consists of numerous rock types encased in a highly convoluted matrix. Adapted from Bob Lillie, 2005.

### Why it's important:

Patrick's Point State Park displays a snapshot of geologic processes that have shaped the face of western North America, and that continue today. The rocks exposed in the seacliffs and offshore represent dynamic interplay between the subducting oceanic tectonic plate (Gorda plate) and the continental North American tectonic plate. The boundary between the subducting oceanic plate and the continent has been filled with a massive pile of material literally scraped off the oceanic floor and crust, partially subducted, and then pasted to the western edge of the North American continent.

ancestral volcanic rocks of the seafloor. The bedrock at the bottom of the Agate Beach trail started out as a neat, orderly package of interbedded sandstone and shale. Forces within the subduction zone tore it apart and created the weak, chaotic rock package we see today. These different types of rocks are often found right next to one another.

Eventually, over millions of years, the material jammed into the trench was compressed between the two plates. Compression then helped to push up the leading edge of the continent, creating the complicated pattern of regional faulting, folding, uplifted terraces and dramatic mountain topography we see today throughout the North Coast region.

## Agates

The popular and prized agates of Agate Beach are resistant pebbles, washed and rounded by stream transport, deposited in sediments along the ancient coastline of North America, and exposed locally by modern wave action.

The source of the pebbles is unknown, but they probably came from volcanic rocks in the ancestral Klamath Mountains to the north and east. Once transported to the ocean via the ancient stream and river system along this part of the California coast, the pebbles were further rounded and polished by constant washing and grinding against sand and each other in the modern surf zone.

### What you can see:

Exposed in the cliffs and sea stacks are complicated layers of mashed and mangled rock. You can look closely at the rock and see folds, fractures, and a variety of layers. These are evidence of the enormously powerful tectonic forces that deform this region.

On a larger scale, you can see the remnants of former seafloor preserved in the sea stacks and flat marine terraces. These forms are evidence of tectonic uplift, sea level fluctuations, and powerful, relentless forces of pounding waves. Waves erode the seacliffs in episodic pulses that peel away vertical slices from the ocean-facing seacliffs.

The agates are composed of quartz crystals (silicon dioxide – SiO2) so tiny that they are barely visible even when viewed under a microscope. Color variations are due to minute amounts of impurities included in the mineral matrix. The variety of color and transparency are a compelling attraction for many park visitors as they sift through the beach pebbles, searching for little treasures that help produce a unique connection to this aesthetic environment.

## Final Thoughts

With repeated visits one may view subtle signs of slow change but we will have to simply imagine how those tiny snapshots in time fit into the never-ending movie that is the geologic evolution of Patrick's Point State Park.

*Written by Jim Falls, California Geological Survey*
*Photos: Shannon Utley*

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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 12

# Sinkyone Wilderness State Park

## Active Fault-Related Features

Active faults at Sinkyone Wilderness State Park include the Whale Gulch Fault and the Bear Harbor Fault zone. The Whale Gulch Fault follows the general trend of Whale Gulch Creek and trends predominantly north of the park. The Bear Harbor Fault is a strike-slip fault and is closely associated with the offshore San Andreas Fault. The Bear Harbor Fault zone is locally well-exposed within the park between the mouth of Whale Gulch Creek and Bear Harbor.

### Features and Processes:

Seismic and coastal geomorphology, and garnet sand

Landforms resulting from fault movement include several sag ponds, linear valleys, shutter ridges, wind gaps and dramatic, sheer ocean bluffs. The landforms related to faulting are most obvious when faults disrupt flat marine terraces. Recent activity

**What you can see:** Sea stacks, garnet sand beaches, fault features, and broad marine terraces are prominent features.

along the Bear Harbor Fault has locally offset the marine terrace—tilting portions of the terrace while leaving other portions relatively flat. At one location near Low Gap Creek, a 4 to 6-foot high fault scarp offsets a marine terrace surface.

Low gradient, linear valleys are most prominent in the northern portion of the park where the Bear Harbor Fault is onshore. The Bear Harbor Fault is part of the nearby King Range Thrust zone and related to the San Andreas Fault, located less than one mile offshore. The Bear Harbor Fault trends offshore near the mouth of Whale Gulch Creek and may be responsible for the very steep and eroding ocean bluff.

Between the area just north of Jones Beach Camp and the mouth of Whale Gulch Creek, the Lost Coast Trail follows an incised linear valley. South of the Visitors' Center, the park road (between Flat Rock Creek and Bear Harbor) is within another linear valley. These fault-related valleys roughly parallel the shoreline and are very close to the ocean bluffs where they are often separated from the ocean by very

**Why it's important:** Sinkyone Wilderness State Park occupies a very distinguished geologic location near the junction of three of the major plates that make up the earth's crust. These three tectonic plates (the Pacific, North American, and Gorda plates) are bounded by major faults, including the San Andreas Fault just offshore of the park, and the Mendocino fracture zone and Cascadia "mega-thrust" (a subduction zone) offshore and north of the park.

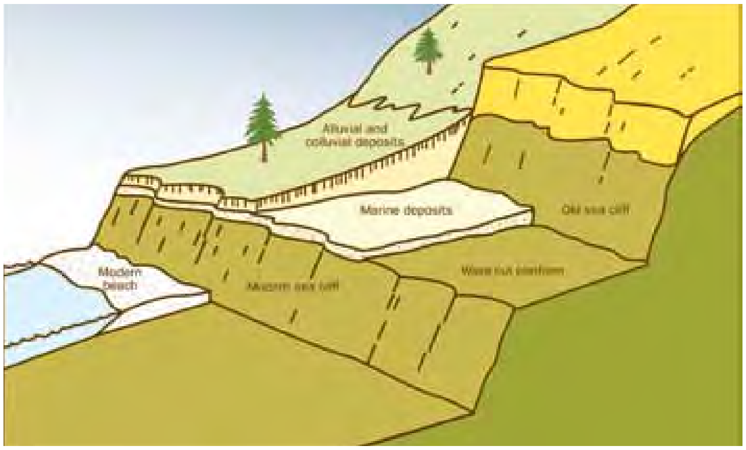
In general, triple junctions are one of the most actively deforming locales in the world—most of which are hidden undersea. The Mendocino triple junction is a broad region that extends onshore into the park and surrounding region—making this one of the most seismically active places in California. There is a long history of very large earthquakes that have thrust this edge of the continent upward.

narrow ridges. In places, water ponds within the linear valleys; these are called sag ponds. Three prominent sag ponds have developed within one linear valley just south of the mouth of Whale Gulch Creek approximately 1.5 miles north of the Visitors' Center. These sag ponds are visible just west of the Lost Coast Trail. The largest sag pond is over 200 feet long and 75 feet wide.

## Marine Terraces

As the King Range has been uplifted above the sea over the past million years, ocean waves have constantly eroded the shoreline. Wave erosion created a nearly flat wave-cut platform that extends offshore. With episodic uplift of the area, the wave-cut terraces are raised above sea level and thus isolated from further wave erosion. The ages of the marine terraces and their present elevation above sea level allow estimates of the long-term rates of uplift.

Wave-cut marine terraces are common between Bear Harbor and the mouth of Whale Gulch Creek. These marine terraces have recently (from the geologic perspective) been uplifted and their ocean-facing cliff edges are youthful. Streams have cut through these terraces, as in the example of an unnamed creek at Jones Beach Camp. The terrace surfaces are relatively flat-lying suggesting they were uniformly uplifted while other terraces are moderately inclined possibly due to local deformation.



**Marine terraces** consist of a wave-cut bedrock platform (bench) with a thin, discontinuous blanket of marine and younger non-marine deposits. The origins of the terraces are tied to changes in climate and associated fluctuations in eustatic (worldwide) sea level during the Pleistocene epoch 11,000–1.1 million years ago. Modified from Weber and Alwardt, 2001.

## Sea Stacks

As waves erode the rising land, creating a wave-cut platform and a sea cliff, they encounter harder rocks. The waves remove the softer, less resistant rocks and leave behind the more resistant, harder rocks which protrude as sea stacks.

Sea stacks are most easily observable from the hiking trails and road between Bear Harbor and Whale Gulch Creek near the northern boundary of the park. Needle Rock can be seen from the top of the bluff near the Visitors' Center. Other sea stacks include Cluster Cone Rock and an emerging sea stack that is still partially attached to the mainland at High Tip. Several of the sea stacks have developed caves or tunnels where ocean waves crash and explode.

## Pink, Purple, and Black Sand Beaches

Purple and pink sand beaches are extremely rare and ephemeral features. The majority of the beaches are composed of black sand (with tiny rock fragments and magnetic grains, such as magnetite and ilmenite), gravel and small cobbles. The beaches are derived from the local bedrock exposed along the base of the ocean bluffs and from sediment delivered to the ocean beaches from the small streams that drain the upland areas.

At times, unusual purple and pink sand beaches appear within the park and then vanish. This special phenomena occurs on the black sand beaches. During unusual wave and tidal conditions, a thin layer of pink and purple garnet sand with uniform grain sizes covers the more ubiquitous black sand—like the frosting on a cake. Offshore, the sloshing action of the waves sorts sand grains according to density and size. Garnet is relatively dense compared to quartz and feldspar which are progressively winnowed away—leaving a relatively pure garnet deposit that disappears when subjected to high tides and storm waves.

**At times, unusual purple and pink sand beaches appear within the park and then vanish.**

## Final Thoughts

The onshore and offshore faulting and related uplift have produced a dramatic and spectacular coastline that continues to change in response to active tectonic plate interactions and sub-aerial erosive forces.

*Written by Don Braun, California Geological Survey*
*Photos: Don Braun*

Prepared by California Geological Survey, Department of Conservation | www.conservation.ca.gov/cgs
for California State Parks | www.parks.ca.gov

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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 13

# MacKerricher State Park

Photo: 2002–2012 Kenneth & Gabrielle Adelman – Adelman@Adelman.com

## Dunes Formation

Sand supply, shore topography, climate, and vegetation determine the location and features of sand dunes. Each of these variables is sensitive to climate change and sea-level fluctuations. Along the California coast up to four major phases of dune formation have occurred since the middle of the Ice Ages (mid-Pleistocene—roughly one million years ago), continuing to about 4,500 to 7,000 years ago and coinciding with a climate period known as the mid-Holocene warm period and its aftermath. More recent phases of dune activity have partially concealed or obliterated earlier dune formations.

**Features:**
Coastal geomorphology,
and geobotany

In MacKerricher State Park, the mid-Pleistocene and mid-Holocene phases have been recognized. Subsequent periods of dune formation occurred approximately 500 to 550 years ago, 936 years ago, during what is known as the Medieval Climatic Anomaly, and about 1,550 years ago. Modern dune processes continue to modify the ancient dunes.

Coastal dunes generally form downwind of major river mouths and against the northwest face of westward extensions of the rugged coastline that block the wind and sand. Coastal streams supply the sediments that are deposited in their deltas.

**What you can see:** Dune fields extend from the mouth of Ten Mile River four and a half miles southward to Lake Cleone. Streams that have been able to maintain flow to the ocean through the dunes divide the dunes into three lobes, producing unique peripheral wetland habitats such as Sandhill Lake and Inglenook Fen.

The sediments are moved from beneath the water and onto land in two primary ways. Waves and currents, especially in the summer, push the sand ashore onto beaches where the wind then blows and moves finer grains. To the north of the park, sand from the mouth of the Ten Mile River is washed ashore and feeds the dunes.

On a vastly different timescale, relative drops in sea level during glacial periods and sporadic coastal uplift periodically exposed parts of the continental shelf and deltas to wind erosion. The flat, broad coastal terraces of the ecological staircase at Jug Handle State Park beautifully show how dramatically relative sea level and land elevations have changed over the past millennia. Subsequent rises in sea level further propelled the sand landward.

Windborne sand is initially deposited around obstacles such as rocks, kelp, debris, and annual plants. As the wind velocity slows around these objects, it drops its load of sand. The initial dune formation begins with small transitory tongues of sand that form on the beach. Sometimes these usually temporary tongues can continue to accumulate sand around plants and form “embryonic dunes” located beyond the upper limits of wave action. As the dunes accumulate sand, the moderate onshore summer winds dry the sand and transport the lightest grains inland. Winds move the sand particles by blowing them up and over the windward (facing the wind) dune slopes. The sand grains are then deposited on opposite (leeward) dune slopes where they are sheltered from the wind. The wind blows the dunes into a series of wave-like dunes. Dunes migrate downwind until stabilized by moisture and vegetation or blocked by obstacles such as forests or steep slopes. Changes in vegetation or climate can remobilize dunes. Streamflow in Inglenook Creek—which forms the fen—adequately flushes advancing dune sand and maintains the drainage to the ocean.

**Why it's important:**
MacKerricher State Park and the Ten Mile Dunes complex contain a unique, relatively pristine native dune and wetland ecosystem.

The effects of climate change over the past several thousand years have been recorded by sediment deposits along the coast. Recurrent periods of dune formation and sea level oscillation have been associated with the Ice Ages and more recent climatic events. These shifting sands of time produced enclosed areas of water ponding that became vegetative microclimates such as Inglenook Fen and Sandhill Lake. The difference between a fen and a bog is that a fen has through-going drainage while a bog does not. Inglenook Fen contains an assortment of plants and insects that are otherwise found to the north from Oregon to British Columbia. The fen is a piece of the puzzle of how climate change induces habitat fragmentation—a key evolutionary concept.

This equilibrium is delicate, and minor changes in climate and stream flow can disrupt the precarious balance.

## Fen Formation

Over the past millennia, natural depressions have formed between the active dunes. The depressions collect water that drains from adjacent uplands. Vegetation establishes in these nascent wetlands receiving nutrients from both runoff and groundwater and over time the wetlands can mature into bogs and fens. A fen is a nutrient-rich wetland which is fed by groundwater.

There are two pathways along which these wetlands mature. One is the progression of an aquatic community to a dryland community. Silt and organic matter accumulate around aquatic plants and create a suitable medium for the growth of fen vegetation. In areas where the water is well-oxygenated and contains a high level of nutrients, the fen vegetation vigorously builds up the soil, which eventually supports a wooded swamp of small tree species, such as willow and alder.

The other pathway to maturity involves the accumulation of organic material that effectively raises the bottom of the bog. This impedes drainage, causes water levels to rise, and allows the bog to expand laterally. Slack water stagnates, becoming oxygen-depleted and acidic enough to be nearly sterile. The accumulating organic matter does not rot due to the general lack of decomposing bacteria and oxygen. Instead the organic matter (known as "sphagnum moss" or "peat moss") compresses under its own weight to become "peat", a juvenile fossil fuel.

## Inglenook Fen

Inglenook Fen is the only known coastal fen in California. It provides habitat for numerous listed species—Menzies' wallflower (*Erysimum menziesii spp. menziesii)*, Howell's spineflower (*Chorizanthe howellii*), and numerous other special status plants. Howell's spineflower is found nowhere else on earth.

*Photo: Mike Fuller*

To explain the unusual presence of plants of more northern affinities in the fen, some have postulated that the fen has provided a microclimatic refuge for its assortment of plants since the last Ice Age (over 11,000 years ago). But preliminary radiometric dates of peat samples taken from near the bottom of the fen suggest formation at 1,000 to 2,000 years ago, and thus do not support the refugia notion. In the park, the oldest discovered peat deposits were found at Lake Cleone and formed approximately 7,000 years ago. Whether the shifting dunes cover even older wetland deposits is unknown. So the mystery remains.

## Final Thoughts

Often geological processes such as dune formation create the topography where organisms eventually find suitable habitat. The fen provides an excellent example of a reverse process where life creates its own environment and becomes a geological force.

*Written by Dave Longstreth, California Geological Survey*
*Photos: Jennifer Lotery (except where noted)*

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# Schooner Gulch State Beach

## Rocks from Points Unknown

Schooner Gulch State Beach is located west of the San Andreas Fault—the boundary zone between the North American continental and the Pacific oceanic tectonic plates. About 25 million years ago, these two huge tectonic plates began to slide past each other along the San Andreas Fault. The oceanic crust to the west of the San Andreas Fault (Pacific plate) has now moved north several hundred miles relative to the continental crust (North American plate) on the east side of the San Andreas Fault.

### Features/Process:

Deep-sea sedimentation, concretions, and effects of differential weathering

Sedimentary rocks in the area of Schooner Gulch and Bowling Ball Beach consist of Miocene-aged rocks (about 10 million years old) locally known as the Gallaway Formation. The Gallaway Formation is one of several that constitute the Gualala Block—an area of rock that crops out near Point Arena along the coast west of the San Andreas Fault. The rocks within the block are believed to have traveled several hundred miles northwest along the San Andreas Fault. Unfortunately, geologists have not been able to find rocks south and east of the fault that match those of the

**What you can see:** During low tide, you can see spherical concretions, “bowling balls”, aligned along bowling alley-like lanes. Close examination of the sedimentary strata that form the “lanes” shows the structures and textures formed by seldom-seen deep oceanic processes. The strata formed through successive episodes of a submarine phenomenon known as density currents in which thick plumes of high density slurries of sediment rapidly flushed across the seafloor and down submarine canyons.

Gualala Block to constrain the actual amount or style of displacement. The Gallaway Formation and the Gualala block are pieces of the geologic jigsaw puzzle that are yet to be resolved.

## Gallaway Formation

The rocks of the Gallaway Formation consist of alternating layers of sandstone, shale, and mudstone. The rocks represent the sediment load deposited on a deep ocean basin. The sediments were flushed off the continent by rivers and washed across the continental shelf as dense slurries in density currents. As the “clouds” of particles settled, they formed layers according to mass—denser ones settled faster and less dense ones landed atop the layers of denser, heavier sediments. After deposition, the weight of the sediments and the precipitation of minerals between the rock particles cemented the grains together and transformed the loose sediment into solid sedimentary rock. The layering is preserved in the rocks that are now somehow at sea level several hundred miles from their place of origin.

## Turbidites

These deposits are called turbidites in reference to the turbulent currents that carried the sediments. Turbidites typically exhibit a sequence of graded beds where coarse sediments (pebbles) are at the base of each sequence of deposition grading upward into sandstone, and then fine-grained shales and mudstones at the top of the deposit. As each new turbidity current flows down the canyon, coarse material is deposited on top of the fine-grained sediment at the top of the previous turbidity flow making very well-defined sequences of sandstones, shales, and mudstones. These represent recurring episodes, with deposits from instantaneous (undersea landslide) events followed by periods of quiescence.

Bedding structures that consist of laminations, ripples and convolutions are preserved in the bedding after the sediments came to rest. At Bowling Ball Beach, turbidite structures exposed in the sea cliff face include convoluted laminations, ripples, parallel laminations, slumps and other structures that can be seen in the individual bedding layers.

**Why it's important:** Geologic oddities can arise from unusual combinations of unrelated geologic conditions. One such example is Bowling Ball Beach where concretions (odd enough in their own right), tilted outcrops of alternating hard and soft strata (not unusual), and wave erosion along the coastline (very common) combine to create a very unusual spectacle.

## Concretions

A concretion is a compact mass of mineral material, usually spherical or disk-shaped embedded in a host rock. Concretions often develop in sediments around the nucleus of organic material whose decay locally changes the pH. This leads to precipitation of a cement around a nucleus (often a piece of shell or fossil). Calcite or silica crystallizes around the nucleus, forming a much harder and more weather-resistant mass than the surrounding host rock. The spherical masses eventually weather out of their parent rock as hard, rounded boulders.

## Bowling Ball Beach

Bowling Ball Beach is located just north of Schooner Gulch. Here the tilted sandstone beds contain concretions that vary from about two feet to five feet in diameter. Some of the concretions have not completely weathered out of the sandstone beds and can be seen high up in the sandstone beds exposed in the sea cliff. Others have weathered out of their sandstone host and are “arranged” on the beach below the cliff. The numerous, nearly vertical beds have been eroded by wave action to form grooves where ridges of more-resistant beds protrude above the softer, less-resistant eroded rock layers. Some of the concretions have been moved, smoothed and polished by wave action and aligned in the grooves, now appearing as bowling balls lined up in a bowling alley.

## Final Thoughts

Like theater curtains that open and close with every act, the tides alternately hide and reveal the geologic stage on the beach.

*Written by Dave Longstreth, California Geological Survey*
*Photos: Jennifer Lotery*

Geological Gems of California State Parks, Special Report 230 – Fuller, M., Brown, S., Wills, C. and Short, W., editors, 2015 Geological Gems of California, California Geological Survey under Interagency Agreement C01718011 with California State Parks.

# Jug Handle State Natural Reserve and Van Damme State Park

*Photo: 2002–2012 Kenneth & Gabrielle Adelman – Adelman@Adelman.com*

## Features/Process:

Coastal geomorphology, and geobotany

## Plate Tectonics

At the edge of the continent, Jug Handle State Natural Reserve and Van Damme State Park occupy the boundary zone between the North American and Pacific tectonic plates. At first, the North American plate overrode the oceanic crust of the Pacific plate, then shifted motion to a lateral grinding that continues to push up the bedrock. The bedrock exposed was scraped, bent, buried, exhumed, and eventually mashed against the North American continent. Bedrock in this region, known as the Franciscan Complex, consists mainly of greywacke (sandstone composed of quartz and feldspar grains incased in a clayey matrix that has been slightly cooked and squeezed).

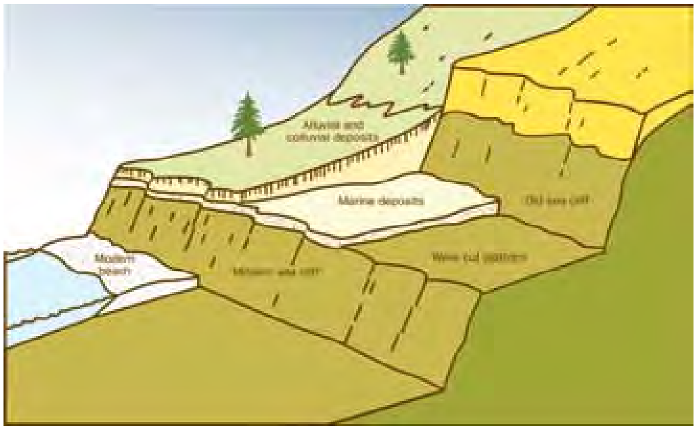
This segment of coastline has risen for about 500,000 years at an average rate of two to three centimeters per century. Movement within the San Andreas Fault zone, which lies about 3.5 miles offshore, contributes to the tectonic uplift.

## What you can see:

Jug Handle State Natural Reserve and Van Damme State Park host a "staircase" of five wave-cut marine terraces formed as a result of tectonic uplift and sea level fluctuations associated with glacial and interglacial periods over the last 500,000 years. Each terrace or "step" contains different ecological communities. The higher steps in the staircase contain "pygmy" forests of miniature bonsia-like trees.

## Marine Terraces Formation

Ocean waves eat away and abrade bedrock surfaces at sea level, gradually creating a gently sloped underwater platform. Steep sea cliffs mark the junction of ocean waves and land. The dynamics between tectonic uplift and sea-level fluctuations created multiple marine platforms (terraces) carved into the Franciscan bedrock.



**Marine terraces** consist of a wave-cut bedrock platform (bench) with a thin, discontinuous blanket of marine and younger non-marine deposits. The origins of the terraces are tied to changes in climate and associated fluctuations in eustatic (worldwide) sea level during the Pleistocene epoch 11,000–1.1 million years ago. Modified from Weber and Alwardt, 2001.

The terraces record the interaction of the slowly rising land with comparatively rapidly fluctuating sea levels. Sea level reacted to the major advance and retreat of glaciers worldwide during the Ice Ages. Sea levels rose during glacial retreats and cut terraces into the coast which were slowly uplifted to their current elevations. With time, sediment from the surrounding uplands spread across on each terrace and its overlying marine sediments creating an additional top layer. The highest terrace in this area is 650 feet above sea level and rising.

**Why it's important:** Some lands are preserved for their scenic beauty or wilderness qualities, but others, such as the pygmy forest, are protected because they are ecologically unique. The sequence of terraces provides a 500,000-year-long timeline of soil and plant community development that demonstrates the interplay of biology and geology like nowhere else.

The terraces support prairies, coastal scrub, bishop pine forest, north coast mixed forest, and pygmy forest. The age of each of the five terraces increases with elevation. Very old soils mantle the uppermost oldest terraces. Soils on these terraces have been leached of minerals (such as calcium, magnesium, potassium and sodium) over hundreds of thousands of years and have formed a hardpan layer cemented with iron oxide impermeable to roots and water. The nutrient-starved plants that do grow are stunted.

## Ecological Staircase

Each "step" (terrace level) of the "staircase" supports a different ecological community depending on the distance from the ocean and the soil type and age. The lowest step in the staircase is the submerged terrace which is still being formed. Kelp, fish, and intertidal communities populate the overlying shallow water.

The second step is the first, elevated terrace (on land). It is the broad, flat bluff overlooking the Pacific Ocean. Rich black, organic soil tops the terrace and supports lupine, poppy, grass and other perennial shrub species. Tree growth is retarded by the salt spray brought by onshore breezes. Redwoods and Douglas-fir dot the eastern edge of the terrace, where salt conditions are tolerable. These trees grow well on the slopes that rise to the next terrace above.

## Upper Terraces

On the upper steps (second, third, fourth, and fifth subaerial terraces), salt spray is not a limiting factor. Over the centuries, strong coastal winds have picked up beach sand and built dunes against the "riser" of each step. Forest vegetation eventually took hold in the dunes through a cyclical process of plant growth, decay, leaching and soil formation. High rainfall (currently 40 to 60 inches per year) percolated through the gradually accumulating organic litter (needles and leaves) and sandy substrate to make a slightly acidic layer of decomposed material called humus. As humic acid leaches nutrients from the humus, it fortifies the underlying sandy soils that nourish the conifer forest.

The midsections of steps consist of beach deposits but lack dunes. The dunes along the back edge impede drainage from the central area resulting in prolonged ponding and, in extreme cases, development of acidic bogs. Sphagnum moss grows in the stagnant bogs which become so low in oxygen and bacteria that dead moss does not decay; instead, it is compressed beneath new growth and becomes peat (a juvenile fossil fuel).

Outside of the bogs and dune areas, strange pygmy forests occur due to the unique soil conditions that stunt growth. Due to the poor drainage and prolonged leaching, the acidified surface soils are depleted of nutrients, while a nearly impermeable mineral hardpan forms beneath. The acidic and nutrient-poor conditions, coupled with shallow hardpan formation contribute to the stunted, sparse growth of the “pygmy” forest.

## Final Thoughts

The ecological staircase and its story of soil development are famous among soil scientists and plant ecologists. Preeminent soil scientist Hans Jenny insisted that places like this should be granted status on a par with art museums and universities. Here, the long ago and far away advances and retreats of glaciers at higher latitudes caused sea level changes which along with tectonic forces formed the terraced topography upon which soil processes and life forces operate to create this unique geological and ecological gem.

*Written by Dave Longstreth, California Geological Survey*
*Photos: Mike Fuller (except where noted)*

# Salt Point State Park

## Tectonic Collision

**Features/Process:**
Seismic and tectonic geomorphology along tectonic plate boundary, exotic terrane, and tafoni

Salt Point State Park lies within the Coast Ranges, the geological equivalent of what an automobile safety engineer would refer to as the "crumple zone", deformed in the collision between the North American and the Pacific tectonic plates. About 25 million years ago instead of colliding head-on, these two plates began to grind sideways past each other along the San Andreas Fault zone. The oceanic crust to the west of the San Andreas Fault (Pacific plate) has moved several hundred miles northward relative to the continental crust (North American plate) on the east side of the San Andreas Fault.

The park spans a section of the collision zone—the San Andreas Fault—and includes pieces of both the Pacific and North American tectonic plates. Metamorphic rocks on the east side of the San Andreas Fault, known as the Franciscan Complex, consist mainly of greywacke (a "dirty sandstone" with significant components of broken rock fragments and sheared silty matrix), shale, serpentine, chert and greenstone that have

**What you can see:** Tafoni and tilted layers of sandstone that formed deep below the sea, 40–60 million years ago and 200 to 260 miles to the south. The rock layers formed through successive turbidity currents—the equivalent to undersea landslides with thick plumes of sediment. The visible grains in the rock layers were suspended particles in those slurries.

*Photo: Mike Fuller*

been slightly cooked, squeezed, and mashed against and onto the North American continental plate. Sedimentary rocks west of the San Andreas Fault, known as the German Rancho Formation, consist of alternating layers of sandstone, conglomerates, and mudstones. These rocks formed in submarine channels and on deep-sea fans at oceanic depths where deep currents deposited mud, sand, gravel, cobbles, and boulders. The weight of the sediment and the precipitation of minerals between the rock particles cemented the grains together and eventually transformed the loose sediment into solid sedimentary rock.

## Tectonic Uplift

The uplifted marine terraces tell a story of spurts of uplift followed by periods of relative tectonic stability. In addition to tectonic uplift, sea level fluctuated about 200 feet or more during the Ice Ages. The sea sent breakers crashing against the solid bedrock, plucking it apart grain by grain. The waves carved away at the bedrock creating a gently sloped platform that terminates in a steep sea cliff landward of the platform. As the polar ice thickened during the Ice Ages, the ocean receded, stranding a mantle of beach deposits on the bedrock-carved shelf, forming an uplifted terrace.

Gerstle Cove Marine Reserve (one of the first protected underwater parks in California) is the site of an embryonic terrace still being formed. It is occupied by tide pool communities that include anemones, starfish, and myriads of bottom-dwelling animals and plants. Kelp and fish communities populate the shallow water that shifts back and forth 10 to 15 feet above the beach deposits. Constant abrasion of sand and gravels against the rock slopes cuts the terrace that someday may be uplifted.

*Photo: Mike Fuller*

**Why it's important:** Salt Point State Park is one of the few parks where the visitor can see well-developed tafoni—a unique sort of rock art created by weathering. How and why tafoni forms remains a geological mystery. The beds that formed from density currents reveal undersea processes and conditions that are rarely witnessed. These exposures are a magnet for study by amateurs, students, and professional geologists. The beds lie immediately west of the San Andreas Fault and provide a key timeline and geologic marker for fault studies.

## Sea Stacks and Differential Erosion

Seacliffs exist because of the destructive force of waves and erosion. The hydraulic force and abrasion created by waves attack the foot of the cliff and begin to erode areas of weakness such as joints, cracks, and faults. Some of the sandstone layers are less resistant to the wind and waves and so are removed faster. Gradually, the erosion may form small caves, many of which can be found along the base of the current sea cliff.

Continued erosion may widen the caves forming arches that may or may not be attached to the mainland. Wave attack at the base of an arch and weathering of the roof of the arch weakens the structure until the roof of the arch collapses, leaving a sea stack (an isolated column of rock). The stack may continue to erode, eventually collapsing to form a stump which may be covered by water at high tide. Finally, the stack may be completely planed away by the waves.

Both recent and ancient sea stacks can be observed in the park. Recent sea stacks are located just offshore where thunderous waves impact the rocks and provide a spectacle of waves, wind, and splash. Ancient and relict sea stacks can be seen on the dry terrace as piles of rocks.

## Tafoni

Salt Point State Park is named for the cliffs and crevices where salt from ocean water crystallizes in sandstone depressions. The native Kashaya Pomo gathered salt here for centuries. Salt crystallization is part of a unique and beautiful type of weathering where rock surfaces are pitted, forming a honeycomb-like network of pockets known as tafoni (the Italian word for cavern).

Precisely how and why tafoni is formed continues to confound geologists, though the presence of saline moisture appears to be instrumental in the process. Splash and spray rinse rock surfaces with saline-rich waters. As salt water evaporates, salt crystallizes between sand grains and small fractures in the rock. The salt crystals loosen sand grains in the less-cemented sandstone. Additional physical weathering (for example wind, rain, and waves) removes the loosened grains to create the lacy, box-like texture on exposed sandstone along the cliff faces.

## Final Thoughts

The restless sea sculpts away at land’s end and is constantly creating new landforms and recycling the materials of old ones.

*Written by Dave Longstreth, California Geological Survey,*
*Photos: Jennifer Lotery (except where noted)*

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# Fort Ross State Historic Park

## San Andreas Fault

The San Andreas Fault extends over hundreds of miles from the Gulf of California north to Shelter Cove near Cape Mendocino. Where it passes through Fort Ross State Historic Park, the San Andreas consists of a number of interconnected fault strands along a zone about 600 feet wide. Geomorphic features indicative of active strike-slip (lateral) movement along the fault zone include elongated hillocks known as pressure ridges and (where they block drainages) shutter ridges. Offset drainages are another common fault-generated feature at the park. A prominent example of an offset creek is the west-flowing Fort Ross Creek, which takes an abrupt turn northward where it encounters a short ridge along the east edge of the fault zone. After a short distance, it turns west again to follow its old course, which has been offset to the north by movement along the fault. The fault's influence on the landscape was dramatically

**Features:**
Seismic and coastal geomorphology along the plate boundary and an exotic terrane

**Why it's important:** The landforms and underlying geology at Fort Ross illustrate a dynamic history of shifting tectonic plates (giant fragments of the earth's crust) and fluctuating sea level. The park is situated at the active continental margin, where the Pacific plate and the North American plate are moving slowly past each other along the San Andreas Fault. To the west, rocks of the Point Arena terrane represent a displaced sliver of the earth's crust that has been dragged northward along the fault for millions of years. East of the fault, entirely different rocks form the core of the northern California Coast Ranges. Marine terraces at the park represent ancient shorelines and sea cliffs preserved though the interplay of climate change and tectonic uplift. Understanding the tectonic processes that helped shape the spectacular setting of Fort Ross enriches appreciation during a visit to the park. The visitor center has interesting historic photos of damage due to the 1906 earthquake.

Before the 1906 quake ...

... and after

Photo: UC Berkeley, Bancroft Library

displayed during the great San Francisco Earthquake of April 18, 1906, when the fault ruptured from south of San Francisco to well north of Fort Ross. Roads and fences in the Fort Ross area were reportedly instantaneously offset between 7.5 feet and 12 feet horizontally, and uplifted on the west side of the fault by as much as three feet. Shaking from the event also triggered landslides in the immediate area.

## Point Arena Terrane

The geologic term "terrane" (distinct and different from terrain) refers to a large fault-bounded packet of rocks with a geologic makeup and history distinctly different from surrounding rocks. Although the Point Arena terrane is traveling northward with the Pacific plate, it isn't truly a part of it. The Pacific plate is composed largely of oceanic crust formed by volcanic eruptions along a mid-ocean rift. Through collisions with the adjacent North American plate, slivers of continental crust and material deposited along the plate boundary were caught up with the Pacific plate, then dragged northward and strung out along the west side of the San Andreas Fault. The Point Arena terrane represents the northernmost of these displaced terranes along the fault.

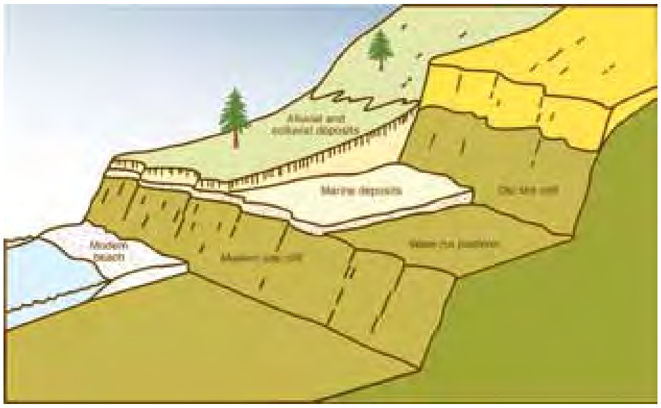
In the Fort Ross area, the Point Arena terrane consists of layered Paleocene to Miocene age (5 to 65 million years old) sedimentary rocks. The rocks are interpreted to have formed from material eroded off the continent to the east and deposited on a submarine fan off the continental shelf. The results of this process are alternating

Photo:: 2002–2012 Kenneth &Gabrielle Adelman—Adelman@Adelman.com

**What you can see:** As Highway One approaches Fort Ross from the south, the road winds precariously along steep mountainsides that descend directly into crashing waves. Shortly before reaching the park, the highway crosses onto a bench that opens up between the mountains and the shoreline. This change in the landscape occurs where the San Andreas Fault trends onshore, and a unique packet of rocks known as the Point Arena terrane emerge along the west side of the fault to form the narrow coastal plain where the fort is located. A close look at this coastal plain reveals a flight of broad "steps" that represent a series of progressively older and more elevated marine terraces cut into the Point Arena terrane bedrock. Along the eastern portion of the park, the presence of the active San Andreas Fault zone has produced abrupt changes in stream direction and formed elongated hillocks.

light-colored sandstone and dark mudstone layers, which can be seen along the cliffs and shoreline below the fort. Other displaced terranes along the fault are notable for the presence of granitic rocks, and have been grouped into what is called the Salinian block. Similarities between granitic rocks of the Salinian block and granitic rocks in southern California indicate the Salinian block likely originated in an area around the northwestern Mojave Desert. Because the Point Arena terrane is located along the west side of the San Andreas Fault, it is commonly regarded as part of the Salinian block. However, the Point Arena terrane does not appear to include granitic rocks, and how far south it may have originated is less clear.

## Marine Terraces



**Marine terraces** consist of a wave-cut bedrock platform (bench) with a thin, discontinuous blanket of marine and younger non-marine deposits. The origins of the terraces are tied to changes in climate and associated fluctuations in eustatic (worldwide) sea level during the Pleistocene epoch 11,000–1.1 million years ago. Modified from Weber and Allwardt, 2001.

Four separate levels of marine terraces have been recognized within the park, with the oldest located roughly 230 feet above sea level. Each terrace consists of a wave-cut bedrock platform (bench) with a thin, discontinuous blanket of marine and younger non-marine deposits. The origins of the terraces are tied to changes in climate and associated fluctuations in eustatic (worldwide) sea level during the Pleistocene epoch 11,000–1.1 million years ago. Wave-cut platforms and sea cliffs formed at interglacial high-stands (peaks in sea level) as wave action beveled the platforms while eroding back the bedrock cliffs. Progressive tectonic uplift of the region lifted the terraces above subsequent sea level high-stands and thereby preserved them. Terraces in the area have been dated and correlated with sea level high-stands between 80,000 and 300,000 years ago. The uplift rate in this region ranges from 0.3 mm to 0.6 mm per year, based on these ages and the current terrace elevations.

## Final Thoughts

Here two powerful land-forming forces (the San Andreas Fault and the surf) meet. The interplay of these forces has produced a landscape full of diverse forms and uncommon beauty.

*Written by Marc Delattre, California Geological Survey*
*Photos: Mike Fuller (except where noted)*

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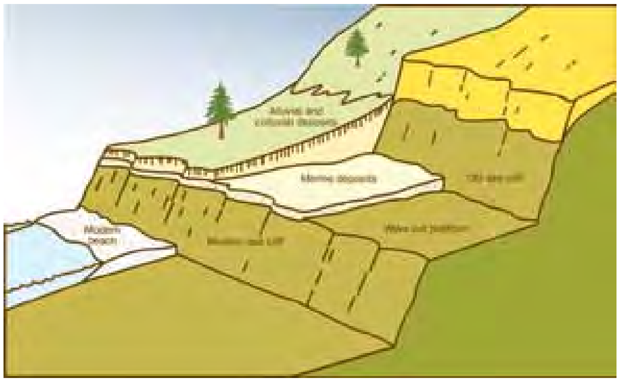
# Wilder Ranch State Park

## Climate and Sea Level Change

**Features/Processes:**
Differential erosion, caves, wave-cut platform

Cyclical changes in climate over the last 1.8 million years were accompanied by fluctuations in sea level due to variations in the amount of water taken up by continental glaciers and polar icecaps. In between some of these hot to cold cycles, worldwide sea level is estimated to have fluctuated by more than 400 feet. Scientists from disciplines as diverse and varied as oceanography, meteorology, paleontology, seismology, and geomorphology have pieced together information on ancient climates, marine terraces, coral reefs and other related issues from around the globe to produce a record of sea level changes through time.

## Wave-cut Platforms Transformed to Terraces



**Marine terraces** consist of a wave-cut bedrock platform (bench) with a thin, discontinuous blanket of marine and younger non-marine deposits. The origins of the terraces are tied to changes in climate and associated fluctuations in eustatic (worldwide) sea level during the Pleistocene epoch 11,000–1.1 million years ago. Modified from Weber and Allwardt, 2001.

The wave-cut platforms and sea cliffs at Wilder Ranch State Park embody ancient shorelines, that existed at peaks (high-stands) in sea level. When the ocean level dropped during a glacial period, the shoreline was left dry and, through continued tectonic uplift of the region, was preserved from being completely erased during subsequent sea level high-stands. Thin mantles of marine sediments with shells, and remains of marine organisms which were present on the platforms when the ocean receded, cover the terraces. With the passage of time, the ancient cliffs eroded to the gentler angles seen today and they shed material onto the marine deposits along their base. The resulting sequence of 1) a wave-cut bedrock platform, 2) an overlying blanket of sandy marine deposits, and usually 3) a mantle of younger material washed from the hillside, collectively form the terraces. This sequence is beautifully exposed along the sea cliffs and in the steep-sided drainages that have cut though the terraces at the park.

**Why it's important:** The park is situated in the California Coast Ranges at the continental margin, a tectonically active zone where the San Andreas Fault system forms the boundary between the Pacific plate and North American plate. As these two enormous pieces of the earth's crust grind slowly past one another, the lands along the plate boundary have been sheared, buckled, squeezed and deformed on a monstrous scale. The Santa Cruz Mountains have developed near where the San Andreas Fault makes a slight bend to the west. As the Pacific plate pushes northward through this bend, it causes compression of the crust, and uplift of the region that is ongoing today. The terraces of Wilder Ranch State Park provide an opportunity to better understand how fast this regional uplift has been occurring.

There are as many as five separate levels of marine terraces preserved in different areas of the park. The terraces increase in age with elevation, and extend to almost 800 feet above current sea level. Through a variety of dating methods, scientists have developed a chronology of terrace development spanning more than 200,000 years. From these data, the rate of tectonic uplift over this period has been between two and four inches per 100 years, providing a good idea of just how tectonically active the area has been.

## Sculpted Sea Caves

Some of the more enticing shoreline features at Wilder Ranch State Park may be attributed to differential erosion. The offshore wave-cut platform and cliffs at the park have been carved into the approximately 20-million-year-old Santa Cruz Mudstone. Cliff retreat is relatively slow along this section of the coast because of the uniform and generally resistant nature of this bedrock unit, together with the protection provided by the offshore platform that absorbs much of the ocean's wave energy. The sandy beaches along this section of the coast are confined to where coastal streams have eroded the cliffs from the landward side. Erosion by the sea is concentrated along zones of weakness within the bedrock, most notably along joints (fractures) and sandstone dikes (near-vertical intrusions of sand injected into the mudstone from deeper sand layers before the rock had hardened). More rapid erosion along these zones of weakness has produced a variety of interesting forms, beginning with surge channels and clefts separating sections of the shore platform. Some of the surge channels advance to form sea caves and arches cut deep into the cliffs, and ultimately may form isolated coves and headlands once caves and arches collapse.

**What you can see:** Looking toward the Santa Cruz mountains, visitors will notice a series of flat-lying areas separated by low, steep slopes. This distinctive landscape of naturally formed terraces represents a series of ancient, shallow seafloors and shoreline cliffs formed over thousands of years that have been gradually uplifted with the elevation of the mountains. This process continues today, as waves slowly erode back the bedrock cliffs of Santa Cruz Mudstone to leave a gently sloping rock platform in their wake. Most of this actively forming wave-cut platform is under water, but portions are revealed at low tide to form the perfect venue for an abundance of captivating tide pools. The usually shear cliff face is occasionally broken by wave-swept sea caves eroded deep into the bluffs, or cut entirely through protruding headlands to form arches. Where small streams meet the sea, the rocky shore gives way to picturesque pocket beaches and inlets.

## Final Thoughts

The dramatic landscapes of Wilder Ranch State Park offer fascinating features to view during a day visit. Experiencing the bold processes that shaped the landscape leaves an impression that endures long after leaving the park, and provides reminders of the dynamic world we inhabit along the California coast.

*Written by Marc Delattre, California Geological Survey*
*Photos: Mike Fuller*

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# Point Lobos State Natural Reserve

National Natural Landmark 1967

## Salinia—An Exotic Terrane

Two contrasting rock types occur at Point Lobos State Natural Reserve. The granitic-rock (porphyritic granodiorite of Monterey) and the sedimentary Carmelo Formation are part of the Salinian block, a strip along California's Coast Ranges, bounded by the San Andreas Fault on the east and other faults on the west. The Salinian block is distinguished by a geologic makeup and history dramatically different from adjacent areas on opposite sides of the terrane-bounding faults. Unraveling the mystery of how this odd block of rocks came to occupy the California coast confounded geologists until the 1960s, when the theory of plate tectonics began to be accepted. Recognizing that the Salinian block as a displaced fragment of the earth's crust was a giant step forward, but the origin of this "suspect terrane" remained to be solved.

**Features:**

Petrology of an exotic terrane along the plate boundary

**What you can see:** The unspoiled coastline at the reserve offers fabulous exposures of two contrasting bedrock units: igneous granitic rock (80 to 100 million years old) and much younger sedimentary rock (60 millions years old).

The granodiorite solidified about 80 to 100 million years ago during the Cretaceous Period, crystallizing from a pool of slowly cooling magma (molten rock) buried deep beneath the earth's surface. The distinctive salt-and-pepper appearance is due to a mix of light (quartz and feldspar) and dark (hornblende and biotite) colored minerals. The term "porphyritic" that is used in the unit's name refers to the igneous texture displayed in the rock, where large crystals (phenocrysts) of potassium feldspar stand out from a groundmass of much finer interlocking crystals. The large phenocrysts found at Point Lobos are unusual for their stretched geometries, with some more than four inches long. Criss-crossing the rock are quartz-filled cracks, dikes (intrusions), and well-developed joints (fractures). The granodiorite is best exposed along the north shore of the reserve, and to the south of Hidden Beach. More rapid erosion along fractures in the otherwise highly resistant crystalline rock has produced the picturesque rocky points, sea-washed clefts, and craggy landscapes found in these areas of the reserve.

Some 60 million years ago (during the Paleocene), after ages of uplift, erosion, and submergence of the granodiorite, the Carmelo Formation was deposited on top of the

**Why it's important:** At Point Lobos, the rocks offer many interesting features for inquisitive visitors to contemplate, but are of particular significance to geologists because they provide clues to decipher movements along the San Andreas Fault system and to the dynamic history that produced the California Coast Ranges.

granodiorite at the mouth of an ancient submarine canyon. Dense mixtures of mud, sand and rocks were periodically funneled down the canyon in fast-moving, turbulent flows called turbidity currents and then deposited in layered sequences known as turbidites. The results of this process are thin alternating light-colored sandstone and dark mudstone layers, with some much thicker conglomerate (rounded cobbles set in sandstone) layers. Imbedded in the turbidites are a few unusually large granodiorite boulders (up to nearly nine feet across), which were likely derived from underwater avalanches or scouring of the canyon walls by turbidity currents.

The Carmelo Formation is best viewed from Sea Lion Point southward to Hidden Beach, and in a portion of Whalers Cove on the north shore. The rocks have been tectonically tilted and washed clean along the shoreline to reveal intricate markings left by the process of deposition (sedimentary structures) and trace fossils (no actual remains, just burrows and trails). Some of the mudstone layers at the reserve reveal curious "feathered" and serpent-like tracks more than six feet long. The tracks are thought to be made by the feeding apparatus of bivalve mollusks related to clams and mussels. These marvelous exposures provide a glimpse into the processes actively at work today in the large submarine canyon located off Monterey Bay.

## Origins of the Salinian Block

The rocks at Point Lobos offer one piece of the puzzle of the locational origin of the Salinian block. The problem is important to solve since by resolving the distance traveled along the San Andreas Fault, geologists can better understand the rate and magnitude of the forces involved. Fortunately there are other pieces of Salinian block to the north and south to help in this enduring mystery.

Comparisons between Salinian granitic rocks and those forming the southern Sierra Nevada and Peninsular Ranges batholiths (large bodies of intrusive granitic rock) have found close affinities in both age and chemistry. Current thinking is that the Salinian rocks formed in the area between these two batholiths, on the west side of the Mojave Desert hundreds of miles away. Starting about 27 million years ago, the rocks were dragged northward with the Pacific plate and brought to their current position by movement along the San Andreas system of faults.

In its journey northward, the Salinian block has been sliced and spread out along the California coast by movement along more than one fault in the system of related strike-slip (laterally moving) faults that form the San Andreas Fault system. Roughly 100 miles north of Point Lobos, a similar sequence of turbidites deposited on porphyritic granodiorite is exposed at the tip of Point Reyes. Comparisons of the rocks from these two dramatic headlands have found them almost indistinguishable, strongly suggesting they were once closer together, but have been separated by movement along the San Gregorio Fault (located offshore from Point Lobos) and the northern portion of the San Andreas Fault.

## Final Thoughts

The landscape of Point Lobos has compelled poets and artists for generations. Notable California poet Robinson Jeffers was inspired by this “devinely superfluous beauty.”

*Written by Marc Delattre, California Geological Survey*
*Photos: Mike Fuller*

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# Montaña de Oro and Morro Bay State Parks

National and State Estuary | State Historical Landmark No. 821

## Strata, Terraces, and Necks

**Process/Features:**
Coastal geomorphology and volcanism

The shoreline of Montaña de Oro State Park is an ideal place to examine and explore geologic features such as tilted and folded rock outcrops. These rocks show different strata that were deposited in horizontal layers sequentially through time. About six million years ago, these beds were deposited as flat layers, one on top of another. The layers of rock record past conditions.

Tectonic forces over the past three million years have tilted the beds. Where these rocks are exposed along the coast, the sloping surface reflects just the top of a thick stack of sloping strata with the oldest beds at the bottom and the youngest beds at the top. Capping the marine strata are gravels that partly covered a marine terrace. These gravels are much younger than the underlying strata and are relatively undeformed. The contact between these two deposits is called an unconformity, and represents an extended gap of time for which the geologic record is incomplete, either due to no deposition or to erasure by erosion.

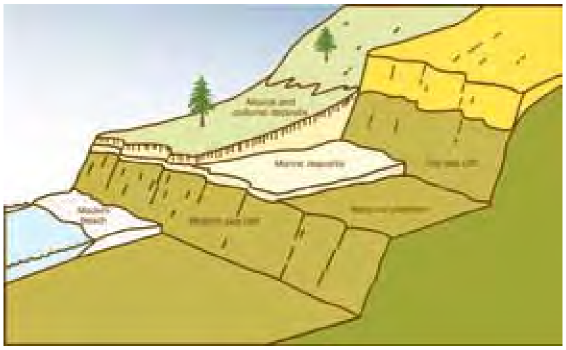
Differential erosion has preferentially etched away the softer rocks, leaving ridges of harder rock as ledges extending into the surf.

**Why it's important:** Morro Bay and Montaña de Oro State Parks are renowned for their spectacular scenery produced over millions of years by volcanic activity, plate tectonic interactions (subduction and collision), and erosion that have shaped this unique landscape.

## Marine Terraces

A sequence of old marine terraces that resembles a staircase leading down to the sea is cut into the slopes of the Santa Lucia Range. Marine terraces are formed by wave action, which erodes the coastline and cuts a marine platform at the base of a sea cliff. The terraces are then preserved due to fluctuations in sea level and tectonic uplift, which raises these surfaces above the sea. The slopes between the terraces were once sea cliffs.

At least 12 distinct marine terraces are found in Montaña de Oro State Park. The most prominent of these, located about 40 feet above the present sea level formed about 80,000 years ago. Older terraces are progressively more eroded, smaller, and less continuous. The oldest of these terraces is a small remnant located nearly 820 feet above sea level. Today, wave action is slowly cutting and widening the marine platform at the modern shoreline and, eventually, this too may be uplifted to form a new marine terrace.



**Marine terraces** consist of a wave-cut bedrock platform (bench) with a thin, discontinuous blanket of marine and younger non-marine deposits. The origins of the terraces are tied to changes in climate and associated fluctuations in eustatic (worldwide) sea level during the Pleistocene epoch 11,000–1.1 million years ago. Modified from Weber and Allwardt, 2001.





**What you can see:** Morro Rock is a volcanic plug, the westernmost part of a chain of extruded and eroded volcanic necks, plugs, and domes that make up the "Nine Sisters", or "Morros." Tilted sedimentary rocks located along the coastline of Montaña de Oro State Park show the succession of rocks that were deposited through time, as well as the effects of tectonic forces that have contorted these rocks after they were deposited. You can also see marine terraces uplifted high above the ocean and an extensive sand spit and dunes.

## Morro Rock

Morro Rock is the westernmost peak in a chain of hills known locally as the "Morros" or the "Nine Sisters." These scenic peaks follow a line that extends between Morro Bay and San Luis Obispo. They are the eroded remnants of a chain of ancient volcanoes that erupted between 20 and 26 million years ago. Using radiometric dating methods, Morro Rock has been determined to be about 21 million years old. It is likely that the nine volcanoes erupted along an ancient fault. Magma flowed up along weak spots in the fault zone where it intruded near the surface or actually erupted.

Volcanic activity ceased. Erosion took over, gradually removing the softer rock that made up the flanks of the volcanoes. Today, all that remains is the crystalline "neck" of the volcano. This neck was originally the conduit for magma moving to the surface.

## Morro Bay

Visitors to the area may be surprised to find out that Morro Bay is a geologically young feature. During the last ice age when sea level was much lower, Morro Bay did not exist since the shoreline was located several miles offshore from its present position. At the time, the area of today's Morro Bay was probably a small river valley. As sea level rose during the last 10,000 years, this valley was inundated. The bay was formed when sand, pushed along the coast by ocean currents, formed the long sand spit that separates Morro Bay from the ocean. Artificial fill connects Morro Rock to the mainland and encloses the northern bay. The entrance to the harbor is regularly dredged to remove the sand that accumulates. This represents the most recent chapter of geologic history that has been in effect for millions of years.

## Final Thoughts

Today, erosion, deposition and ongoing tectonic forces continue to shape this rugged and evolving coastline.

*Written by Tom Dawson, California Geological Survey*
*Photos: Alan Schimierer*

Geological Gems of California State Parks, Special Report 230 – Fuller, M., Brown, S., Wills, C. and Short, W., editors, 2015 Geological Gems of California, California Geological Survey under Interagency Agreement C01718011 with California State Parks.

# Point Sal State Beach

National Natural Landmark 1974

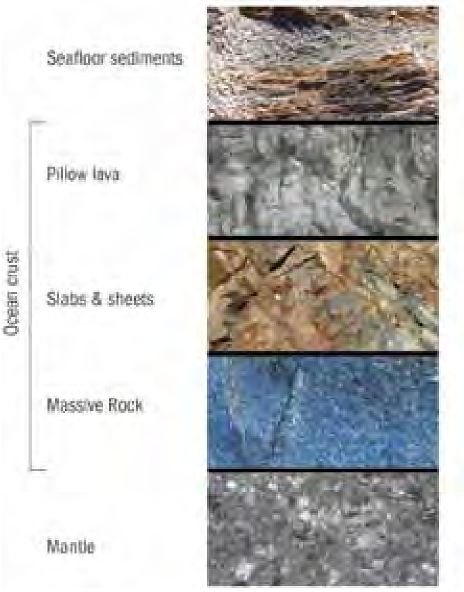
## A Window into the Deep Earth

The exposed rocks along the coastline of Point Sal make up what is known as the Point Sal Ophiolite, part of the Coast Range Ophiolite. An ophiolite is a slice across the layers of seafloor (as produced at a mid-oceanic spreading center) from the basement rock to the overlying accumulations of volcanic and sedimentary rocks. At Point Sal and to the south, an approximately three-mile thick section of ophiolite is exposed on land.

**Feature/Process:**

**Petrology of an ophiolite and pillow lava**

During ophiolite formation at the spreading center, molten rock (magma) from below the thin oceanic crust penetrates into seafloor fractures and either slowly cools and solidifies below the surface or erupts onto the surface as lava. The lava cools abruptly when it encounters the oceanic waters and forms rounded blobs. Outcrops of such lava can look like a stack of pillows, called pillow lavas. Molten rock that cools beneath the pillow lava forms as slabs of fine-grained rock. Radiometric dating shows that these volcanic and intrusive rocks formed during the Jurassic Period, about 165 million years ago. At structurally deeper levels of the crust, massive intrusive igneous rocks such as diorite and gabbro are found. Below these igneous intrusions are rocks that represent the upper mantle and consist of dunite and peridotite. These coarse-grained rocks represent the basement of the oceanic crust.

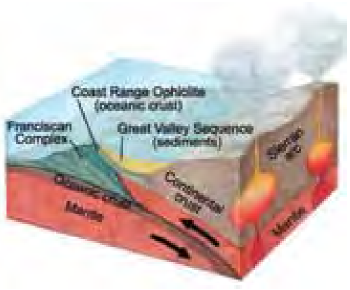


**Ophiolite:** A layered assemblage of rocks that formed as a section of oceanic crust. The crust forms at rifts in the oceanic crust such that a characteristic sequence of layers is formed. The rate of cooling of molten rock is controlled by the depth below the ocean floor where water quenches the rock. The deeper layers are cooled more slowly while the uppermost layers cool rapidly. Pillow basalts typify the upper layers while intermediate layers develop as vertical slabs and lowermost layers develop as massive rock.

## A Journey Across the Ocean

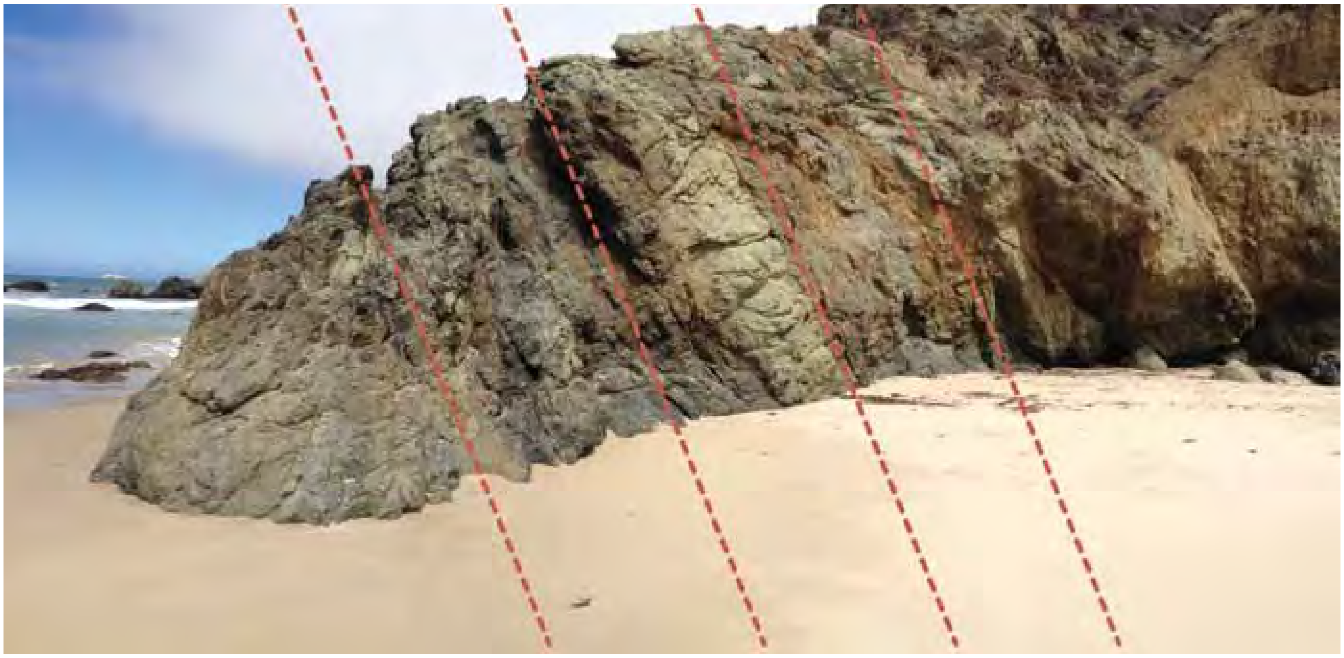
When the lavas erupted, they were located at a mid-ocean spreading center. Geologists have studied the magnetic "signatures" of these lavas and have determined that the mid-ocean spreading center where these rocks formed was near the equator. Rocks found above the pillow basalts tell the story of how the ophiolite migrated from the equator and became attached to the margin of North America. Limestone (formed from the skeletal remains of ancient sea creatures) was the first rock to be deposited on top of the pillow lava. The limestone was most likely deposited in warm tropical waters. As the ophiolite was carried away from the spreading center by plate tectonics, the ocean floor became deeper, too deep in fact, for limestone to form. Bedded chert, a reddish sedimentary rock that is made of the skeletal remains

**Why it's important:** The rocks that make up Point Sal represent one of the most intact and complete cross sections of oceanic crust visible on land. Oceanic crust comprises 60% of the earth's crust, yet we rarely have opportunities to see it and study its formation. The rocks at the park indicate submarine origin and widespread transport via plate tectonics.



*Graphic by Lillie, 2005.*

Oceanic crust is produced at ocean spreading centers and consumed in subduction zones. This process recycles oceanic crust and destroys the evidence of its creation. Oceanic crust older than 170 million years is exceptionally rare. Point Sal and outcrops like it have escaped the recycling process and preserve the only evidence of the geologic history of older oceanic crust. Geologists are trying to understand how these fragments of oceanic crust avoided re-cycling and became exposed at their present locations. This history is shared by many of the rocks that make up the Coast Ranges throughout much of Central California.



**What you can see:** An exposed cross section of ancient seafloor and oceanic plate that traveled (as part of the Pacific plate) from its apparently tropical “birthplace” at an oceanic rift to the central California coast. Layers may appear obscure but upon close examination are evident; red dashed lines clarify the ophiolite component layers.

of small sea creatures called radiolaria, was deposited on top of the limestone. Interbedded with the cherts are layers of volcanic ash, erupted from volcanoes that likely existed along the western margin of North America. Recent studies suggest that this occurred at the latitude of Baja California.

## Forming the Coast

The ophiolite is encased within the Franciscan Complex, a chaotic assemblage of rocks scraped off of the subducting Farallon plate as it was thrust beneath the Coast Range Ophiolite (CRO). This wedging of Franciscan Complex materials under the CRO had the effect of uplifting coastal California. To the east, sediments (the Great Valley Sequence) shed off of the margin of North America were deposited on top of the CRO.

The most recent chapter of this story began in the Tertiary epoch (approximately 20 million years ago) as subduction waned and the current tectonic regime of San Andreas-style faulting began.

During these processes, the CRO broke into pieces. Movement along the San Andreas Fault system continues to spread fragments of the ophiolite along the coast.

Photo: 1989, Kenneth and Gabrielle Adelman – Adelman & Adelman.com

## Landslides

During the El Nino rainfall events from the mid to late 1990s, landslides and gully erosion caused closure of the access road to Point Sal State Beach. Now the road is passable by foot only. The landslides are extensive in the Miocene-aged sediments that overlap the rocks of the ophiolite. The ocean waves redistribute slide debris that accumulates on the beach maintaining a smooth beach. But the larger waves attack the base of the landslides increasing the instability. Geologically the state beach occupies a narrow strip in an amazingly dynamic environment with highly unstable slopes on one side and the crashing waves of the ocean on the other.

## Final Thoughts

Fortunately, plate tectonics has left a largely intact piece of ophiolite at Point Sal, making it one of the premier locations to observe the rocks that record the formation and history of coastal California.

*Written by Tim Dawson*
*Photos: Will Harris (except where noted)*

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# Klamath Mountains Geomorphic Province

The **Klamath Mountains** consist of several rugged ranges and deep canyons. The mountains reach elevations of 6,000 to 8,000 feet. In the western part of the province, the irregular path of the Klamath River is incised into an uplifted plateau often referred to as the Klamath peneplain. The uplift has left successive benches with gold-bearing gravels on the sides of the canyons. The province is considered to be a northern extension of the Sierra Nevada. Rocks include metamorphosed Paleozoic and Mesozoic oceanic rocks, abundant serpentinite, and granitic intrusions.

## Tectonic Setting

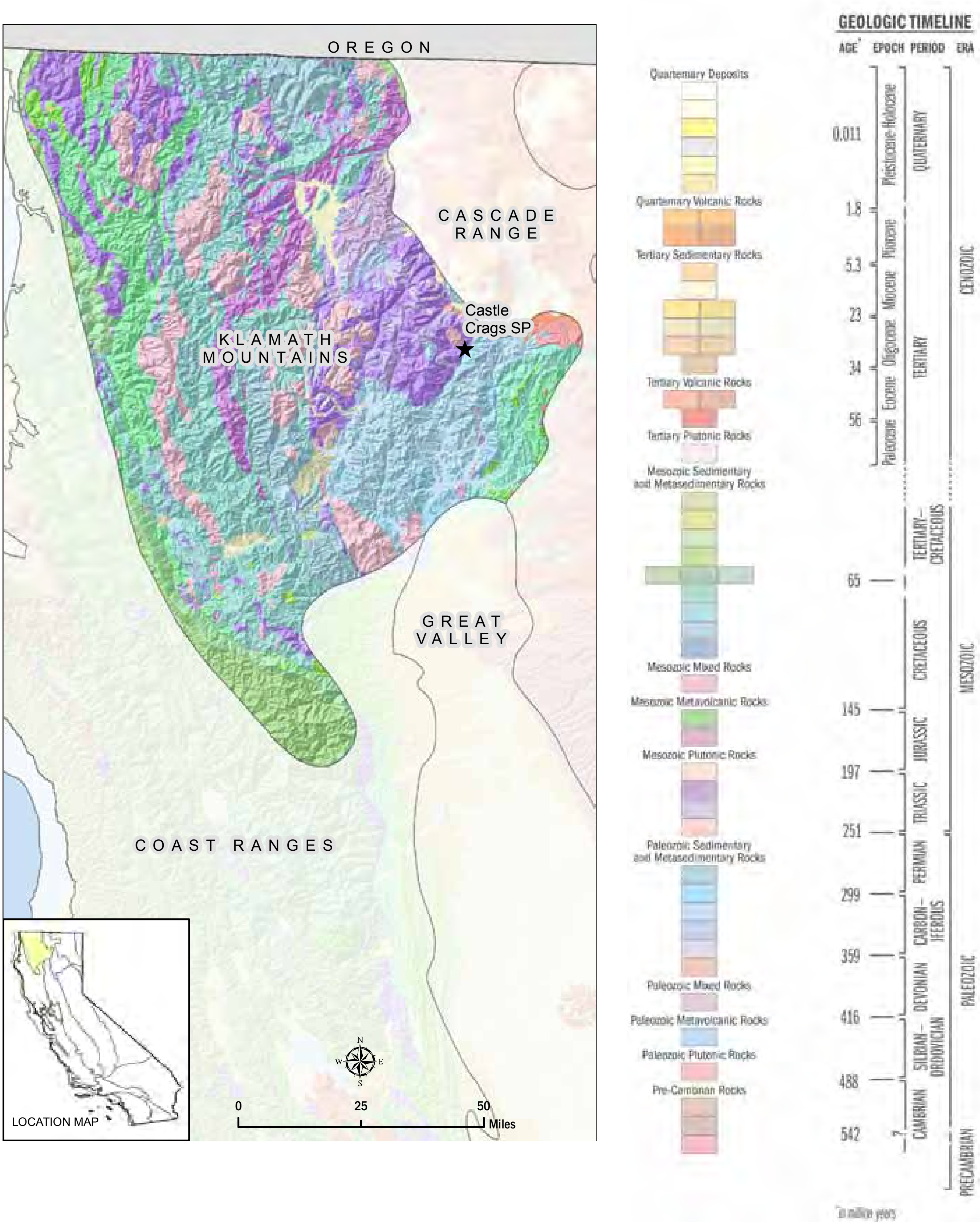
The oceanic rocks and serpentinite represent accreted terranes with the latter being interpreted as an ophiolite. Several distinct terranes have been identified. The terranes have been intruded by granitic plutons and veins. Veins, which crosscut adjacent terranes, formed after accretion and help constrain the history. Studies that dated rocks in the province show the terranes are progressively younger from east to west, ranging from Devonian to Late Jurassic Periods (416 to 190 million years ago.)

## GeoGem

**Castle Crags State Park** is the lone GeoGem representing the Klamath Mountains province. Its granitic monolith resembles those in Yosemite National Park. The granitic rock of Castle Crags formed probably one to two miles beneath the surface about 160 to 165 million years ago as a slowly cooling molten body called a pluton. Molten magma that rose along fractures to the surface probably fed volcanoes similar to nearby Mount Shasta. Castle Crags State Park lies near the eastern boundary of the Klamath Mountains geomorphic province near the western edge of the Cascade Range. Stunning views of the snow-capped volcanic giant Mount Shasta dominate the landscape.

*Written by Mike Fuller and others, California Geological Survey*
*Photos: Christopher Mizeur*

## Simplified Geologic Map | Klamath Mountains Geomorphic Province



**NOTES:**

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

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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 23

# Castle Crags State Park

## What are the Crags?

The Castle Crags are in the Klamath Mountains geomorphic province, which consists of multiple fragments of oceanic crust that have been transported to and added on (accreted) to the western edge of the North American continent by plate-tectonic processes. Rocks immediately surrounding Castle Crags consist mostly of Ordovician-aged (443–490 million year old) oceanic crust referred to as the Trinity ultramafic sheet. Ultramafic implies high concentrations of iron and magnesium.

**Process / Feature:**

Weathering and petrology of an ophiolite and a zoned pluton, and crags

The edifice of Castle Crags resulted from the intrusion of a granitic magma into the ultramafic rock around 160 million years ago. Millions of years of erosion have exposed the rock and shaped the picturesque spires and domes of the Castle Crags.

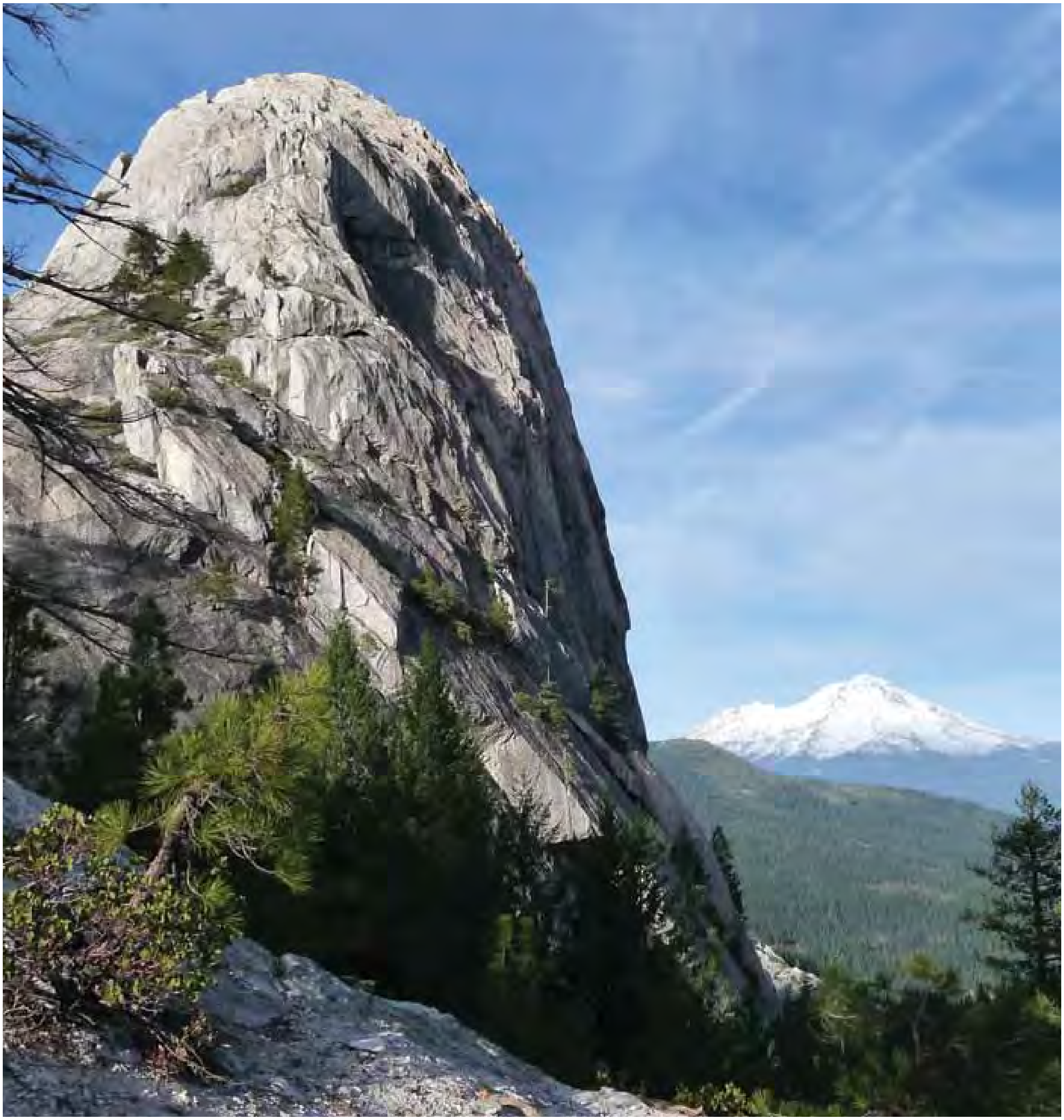
## Zoned Pluton

Molten masses (magma) of igneous rock deep inside the earth's crust are referred to as plutons. Plutons often form as a product of rocks melting to magma deep in a subduction zone. Just as hot air tends to rise, plutons rise through the crust and cool. Over the course of many years, the magma eventually solidifies under the crust. Some of the magma may escape to the earth's surface in the form of volcanoes and lava. During the formation processes, the magma may segregate into zones of differing compositions as pressures and temperatures change. Once solidified, the differing compositions become different rock types with unusual names to distinguish them. The term "granite" is frequently used as a family name to refer collectively to various, yet specific igneous rock types.

The granitic monolith of Castle Crags is the remnant of a pluton. Castle Crags is composed of different types of granitic rock, representing different parts of the pluton. Trondhjemite and granodiorite form a core and shell, respectively. Slow cooling of the magma resulted in a concentric zoning of the pluton that is preserved and exposed in the Castle Crags rocks. The outer part of the magma cooled relatively rapidly where it was in contact with the surrounding ultramafic rocks, resulting in relatively small crystals of the rock-forming minerals. The rapid cooling around the outside of the newly-intruded pluton formed a insulating blanket of fine-grained granodiorite around the remaining magma. Slower cooling of the magma beneath the "blanket" gave the granitic crystals in the remaining magma more time to grow, producing large crystals of rectangular-shaped pink potassium feldspar prominent in the bulk of the exposed pluton.

As the magma cooled and crystallized even more, volatile gases (mostly water) contained in the magma became increasingly concentrated until the volatile concentration became so great that the remaining liquid magma "boiled". That is, the gases came out of solution and formed small bubbles in the remaining liquid magma. The resulting small bubbles are now exposed in the solidified rock as an extensive zone of well-developed "miarolitic" cavities found along the boundary between granitic rocks containing the larger potassium feldspar crystals and the trondhjemite core of the pluton.

**Why it's important:** Few of California's state parks display impressive monoliths adorned like a castle with towering spires, and few permit rock climbing. Castle Crags is an exception. The scenic beauty is best enjoyed from a distant vantage point where one can see the range of surrounding landforms. The monolith and its surroundings are a microcosm of the Klamath Mountains where many such monoliths intrude and stitch together a crazy quilt of much older rocks. The surrounding rocks include the Trinity ultramafic sheet, the largest exposed body of ultramafic rock in North America. The ultramafic rock is often interpreted to represent an ancient ophiolite—a slice of the oceanic crust.



**What you can see:** The towering light-colored granitic spires and domes of Castle Crags can be seen from the park, but are actually outside of the state park boundaries. The light-colored, erosion-resistant peaks stand out in stark contrast to the darker-colored, less-resistant ultramafic rocks (peridotite and serpentine) and sedimentary rocks underlying adjacent hills, and the towering presence of 14,162-foot-high, snow-capped Mount Shasta.

The scenic grandeur viewed from trails within the park is unrivalled, ranging from close-up views of the majestic spires and domes of the Crags, to distant vistas of the Cascade volcanoes of Mount Shasta, Mount McLaughlin, and Mount Lassen.

## Exposure

After the igneous rock cooled completely and solidified, the rocks overlying the pluton were eroded by running water, landslides, and by glaciers, removing miles of overlying material and eventually exposing the bare rocks of the Castle Crags pluton. Because ultramafic rocks are less resistant to weathering than the granitic rocks, the more easily weathered ultramafics eroded at a faster rate, leaving the more resistant granitic rocks to protrude above the surrounding lands, forming the Castle Crags, the tops of which tower more than 4,000 feet above the surrounding landscape.

## Final Thoughts

The state park's strategic location assure enduring access to a beautiful geological treasure, and provides entry to a federally protected wilderness area, with abundant glacially carved features.

*Written by Michael Wopat, California Geological Survey*
*Photos: Christopher Mizeur*

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# Cascade Range Geomorphic Province

Photo: Shannon Utley

The **Cascade Range**, a chain of volcanic cones, extends from southern British Columbia through Washington and Oregon into northern California. Cascade volcanoes are large cone-shaped mountains built by very explosive eruptions that produced extreme volumes of ash deposits. In California, Mount Shasta, a glacier mantled volcanic cone, rises 14,162 feet above sea level and is one of the world's largest composite volcanoes. At the southern end of the Cascade Range is Lassen Peak, a very large plug dome, which last erupted during the period of 1914 to 1921. Between these two volcanic centers, the Cascade Range is transected by the deep canyon of the Pit River, which eventually joins with the Sacramento River. Prehistoric eruptions within this mountain range left several enormous calderas, such as Crater Lake and the area partially occupied by Mount Lassen.

Just 30 miles east of Mount Shasta lies Medicine Lake volcano, a large shield volcano—so named for its broad and rounded, low profile. Despite its low profile, it is believed to be the largest of the Cascade volcanoes. Medicine Lake occupies a large caldera. Its different shape relates to the less viscous (more fluid) magma that feeds it.

Photo: Chris Wills

## Tectonic Setting

The Cascade volcanic rocks result from the subduction and partial melting of the Gorda tectonic plate in the active Cascadia subduction zone. The Mendocino triple junction marks the southern limit of the subduction zone. Many of the Cascade volcanoes are either active or potentially active.

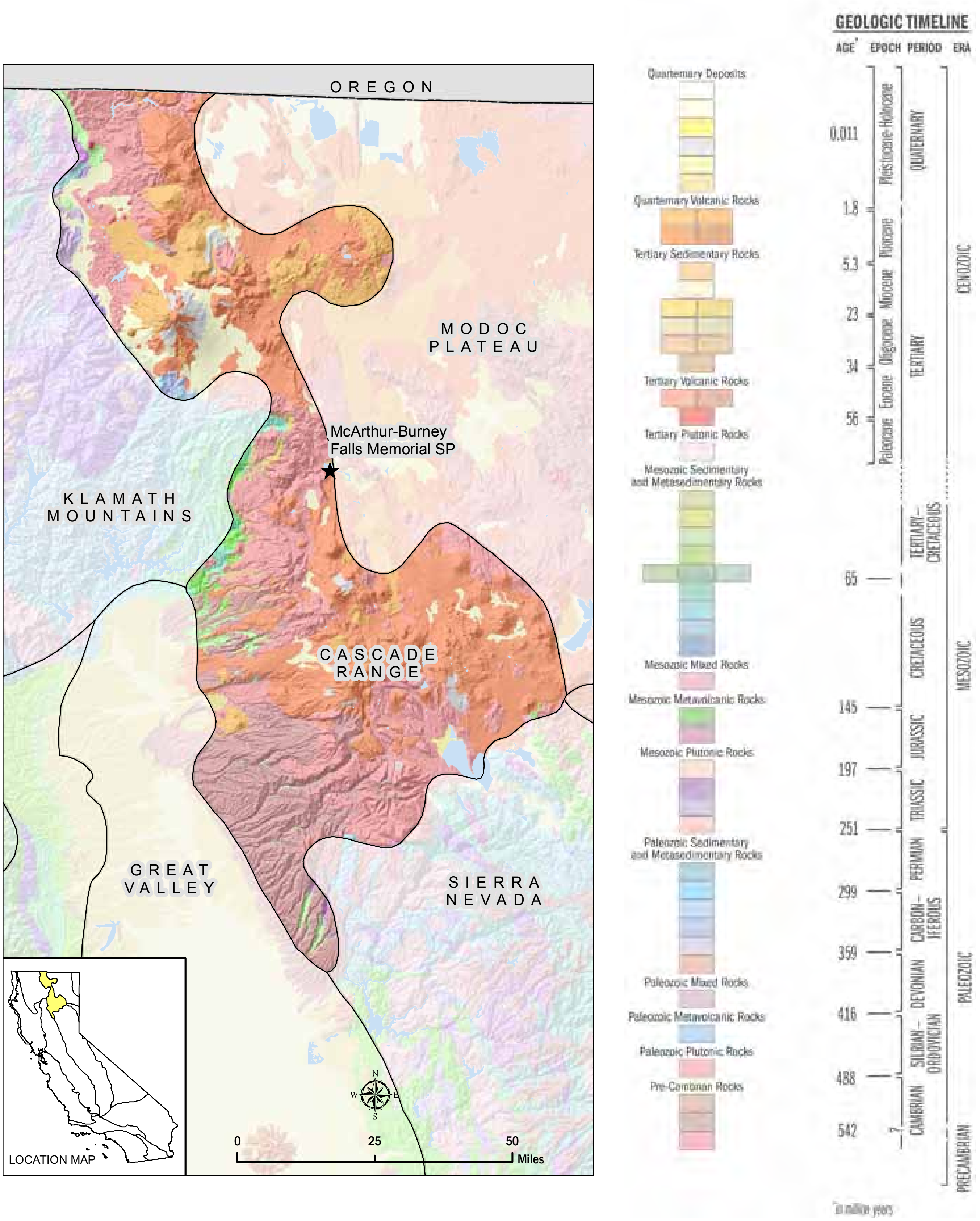
At Medicine Lake, the magma and style of volcanism is more characteristic in regions undergoing crustal thinning and extension such as in the Modoc Plateau and the Basin and Range provinces. But it also shows characteristics of the Cascades. This is an excellent example of overlap in geomorphic boundary zones.

## GeoGem

**McArthur-Burney Falls Memorial State Park**, like Ahjumawi Lava Springs State Park, is along the boundary between the Cascade Range and the Modoc Plateau geomorphic provinces. The flat-lying lava flows that blanket the park are a few million years old, similar to the flows that cover much of the Modoc Plateau. Like Ahjumawi Lava Springs State Park, much of the water flowing over Burney Falls originates as groundwater that flows mostly in fractures, openings and cavities of the volcanic lava deposits.

*Written by Mike Fuller and others, California Geological Survey*

## Simplified Geologic Map | Cascade Range Geomorphic Province



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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 25

# McArthur-Burney Falls Memorial State Park

National Natural Landmark 1984

## From Lava Flows to Waterfalls

Burney Falls is in the eastern part of the Cascade Range geomorphic province near the boundary with the Modoc Plateau geomorphic province. Lava flows superficially blanket both provinces. The falls are at the north end of a west-northwest oriented basin in a region of several faults that run north-northwest. Most of the rocks in the vicinity of the falls are basaltic lava flows. Basalt rocks underlying the higher areas west of the park are Pliocene in age (5.3 to 1.8 million years old) and those underlying the park itself are Pleistocene in age (1.8 million years old or younger).

**Features/Process:**

Volcanic hydrogeology of waterfalls, and lava flows

The lava flows repeatedly covered the ground surface and built up the plateau layer by layer. Hot gases within the fresh lava bubbled to the top of some layers to form a froth that quickly solidified in the cooler environment of the ground surface conditions. The frothy sponge-like layer is called scoria and is easily broken apart into small fragments. As the lava flowed, the surface margins cooled while the inside remained molten, flowing out to create interior channels known as lava tubes. As flows cooled throughout, extensive cracks formed due to thermal contraction. Earthquakes were common and fractured the solidified lava rocks. These features provide abundant pathways and storage spaces for groundwater and are key factors underlying the voluminous spring-fed water flows that emerge at the falls. With time, the minerals of the basalt gradually break down into clay particles which will eventually clog the spaces and pathways. Such is the case with the older Pliocene lava beds to the west.

## Sources of the Water

The ultimate source of the water in Burney Falls is the rain and snow that falls over the Pit River watershed. The water either flows directly into the creek or soaks into the sponge-like rocks. During times of high water, the creek flows continuously all the way to Burney Falls. During drier times, Burney Creek commonly sinks into its bed, disappearing well upstream of Burney Falls, only to reappear as seepage into the creek bed above the falls and as springs in the rock face of the falls.

In the summer, the farthest upstream spring is about ¾ mile from the lip of the falls. The Burney creekbed is usually dry from that point on upstream.

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**What you can see:** The highlight is Burney Falls, a 129-foot tall thundering waterfalls fed both by a spring-fed stream (Burney Creek) flowing over the top of basalt cliffs and by springs that issue directly from the basaltic cliff face. The springs are reported to discharge approximately 100 million gallons per day.

The 1¼-mile long gorge downstream of the waterfalls was carved by progressive stream down-cutting and undercutting of weak rocks that underlie the durable basalt flow.

Around the south side of Lake Britton are exposures of a soft white rock (diatomite) also found in the gorge downstream of the falls.

*Photo: Dennis Heiman, Sacramento River Watershed Program*

**Why it's important:** Burney Falls is an outstanding example of a waterfall and stream fed by large springs that are commonly associated with areas covered by recent lava flows, and also of a waterfall formed by the undercutting of horizontal rock layers.

The soft white rock is diatomite. Its presence is evidence that a very large lake once filled the region and supported abundant tiny freshwater plankton called diatoms.

## Permeability (a measure of how efficiently water can transmit through rock)

Pleistocene and Holocene lavas flows exhibit moderate to very high permeability. They contain open joints and fractures that serve as passageways for the downward migration of water. Water also migrates through various rock units: 1) highly permeable volcanic-rock rubble, and/or 2) scoria at the surface and base of the layers, and 3) stream gravels in drainages down which the lava may have flowed.

The basalts have been locally disrupted and fractured by earthquakes along faults. A number of faults immediately south and southeast of Lake Britton are considered still active in that they exhibit movement in Holocene (11,000 years old or younger) time. The movement along the faults offsets the basalts into tilted blocks. The blocks are separated by nearly vertical scarps ranging in height from 10 to 100 feet or more. The rock is sheared along these faults, producing highly permeable pathways for the infiltration (downward movement) of groundwater.

In the park, surface streams are relatively rare since water soaks readily into the highly permeable Pleistocene lava flows. Once subsurface, the water (groundwater) flows laterally along the permeable tops and bottoms of the lava flows and in sediments between lava layers. Groundwater commonly resurfaces as large springs, such as those that feed Burney Falls, Hat Creek to the southeast, the Fall River at Thousand Springs, and Big Lake a few miles northeast of Burney Falls.

In contrast, the older, more-weathered Pliocene lava flows exhibit less permeability because the clays formed by weathering of the lava seal the porous voids within the lava flows.

## Differential Erosion

The gorge below Burney Falls was formed by erosion of the softer layers beneath the Pleistocene basalt flow. The continual erosion of these softer strata by the relentless pounding forces of the waterfall undermines (removes support for) the overlying lava flow, causing it to periodically collapse into the developing gorge. By this process, the waterfall migrates upstream. So far, it has migrated more than a mile from the confluence of Burney Creek and the Pit River (which is now impounded behind the hydroelectric Pit No. 3 Dam as Lake Britton).

## Diatomite

In the park and especially to the north, 1.8 to 5.3 million-year-old rocks that consist largely of a chalky white substance (diatomite) underlie the younger lava. The diatomite consists of skeletal remains of microscopic single-celled plankton that were abundant in an ancient lake, died, and sank to the bottom. The lake likely filled behind a natural dam or dams formed by movements along faults. The local diatomite is a small example of the much more widespread deposits in the region. Their broad distribution suggests that the lake in which they formed may have been quite large. How large? That remains unknown.

Diatomite has commercial applications including use as a filtering agent, as filler for paints and spackle, as an addition to cement, and as a mild abrasive. It has been mined at the large Dicalite Mine just west of Lake Britton—outside of the park.

The younger Pleistocene lava flows erupted, flowed over, and covered the diatomite.

## Final Thoughts

The past landscape has been covered and obscured by lava flows and modified by erosion to its current incarnation. But the landscape continues to change as it is subjected to geological processes, and eventually it will be destroyed and re-constructed to a fresh, new look.

*Written by Michael Wopat, California Geological Survey*
*Photos: Michael Wopat (except where noted)*

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# Modoc Plateau Geomorphic Province

The **Modoc Plateau** is a volcanic tableland with elevations ranging between 4,000 and 6,000 feet above sea level. Most of the volcanic rocks erupted as extensive fluid lava flows during the Tertiary period, between 10 and 2 million years ago. The Modoc plateau eruptive centers consist of fissures and many small cones. Eruptions were nowhere near as explosive as the Cascade volcanoes. Instead, the volcanic products consist of a thick accumulation of lava flows and tuff/ash beds that have built the plateau. Many northerly-trending faults cut across the plateau, breaking it up into tilt-block mountains.

## Tectonic Setting

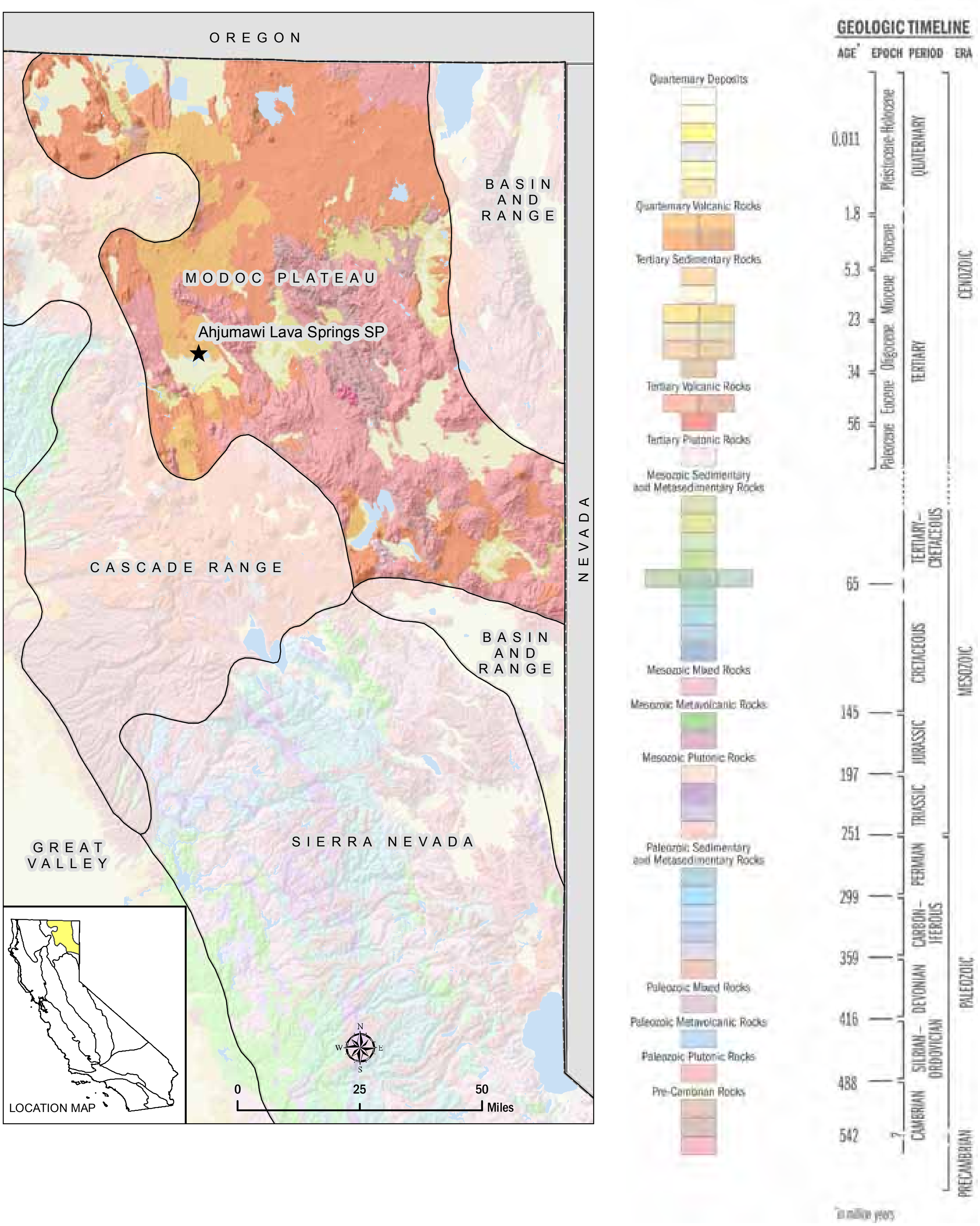
This style of volcanism occurs in regions experiencing crustal thinning and extension such as in the Basin and Range geomorphic province to the east. The region consists of 1) Tertiary and Pleistocene basalt lava flows with more recent flows at the edge of the Cascade Range geomorphic province, and 2) closely spaced, northerly-trending faults characteristic of the Basin and Range province. The Modoc Plateau geomorphic province can be thought of as a broad boundary zone between the Cascade and Basin and Range provinces.

## GeoGem

**Ahjumawi Lava Springs State Park** occupies one of those enigmatic geomorphic addresses that share characteristics with multiple geomorphic provinces—the Cascade Range, Basin and Range, and the Modoc Plateau. The interplay of water and rock combine to create a unique geologic/hydrologic environment at Ahjumawi Lava Springs State Park. Rain and snow that fall on the Medicine Lake Volcano to the north of the park sink into the fractured volcanic rock, resulting in a hard-edged, dry volcanic landscape mostly devoid of surface streams. The park preserves the refreshing linkage between the atmosphere above and the earth below as the groundwater that has percolated down from the Medicine Lake Volcano emerges as springs, marshes and lakes.

*Written by Mike Fuller and others, California Geological Survey*
*Photos: Michael Wopat*

## Simplified Geologic Map | Modoc Plateau Geomorphic Province



NOTES:

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

Geological Gems of California State Parks, Special Report 230 – Fuller, M., Brown, S., Wills, C. and Short, W., editors, 2015 Geological Gems of California, California Geological Survey under Interagency Agreement C01718011 with California State Parks.

# Ahjumawi Lava Springs State Park

## Lava Flows and Springs

Ahjumawi Lava Springs, along with numerous other springs, discharge along the edges of a lava plateau composed of dark lava that flowed southward from the Medicine Lake Highland, a shield volcano. Lava flow after flow eventually built the plateau.

**Process / Feature:**
Volcanic hydrogeology of massive springs, and lava flows

The plateau can store enormous amounts of groundwater within abundant fractures, lava tubes, seams between layers, and thick (30 to 500 feet) masses of cinders. In fact, these rocks can absorb rainfall and snowmelt into the subsurface so quickly that surface water flow is virtually nil. The total flow of springs issuing from the lavas at the north end of Fall River Valley has been estimated to range from about 600 million gallons per day to as much as 1.3 billion gallons per day.

The basaltic flows along the north side of Ahjumawi can be accessed by several trails past volcanic features such as spatter cones, lava tubes, basalt outcroppings and collapse depressions. The public access for the park is exclusively over water, from Big Lake, Horr Pond, Ja She Creek and the Tule River.

**Why it's important:** "Ahjumawi" means "where the waters come together" in the Ajumawi language. This is a particularly appropriate description, since the waters of Big Lake, Tule River, Ja She Creek, and Fall River all come together at this location. The springs at Ahjumawi Lava Springs State Park comprise one of the largest fresh water spring systems in the country. They discharge into Big Lake, Horr Pond, and Ja She Creek, which together form the headwaters of the East Fork of the Tule River (a major tributary to Fall River).

**What you can see:** Volcanic deposits and features from Holocene eruptions from the Medicine Lake Volcanic Highland to the north, and one of the country's largest freshwater spring systems, which feeds the headwaters of Fall River and Tule River.

Rugged basaltic lava flows, spatter cones, lava tubes, craters, evidence of faulting, majestic views of distant volcanoes (Mount Shasta and Mount Lassen).

## Water Chemistry and Origin

Many have wondered where the huge amount of water originates. Tule Lake, Klamath Lake, Little Valley Hot Spring, and Medicine Lake seem like likely suspects based on circumstantial evidence. But chemical differences seem to have ruled out each of these. The springs may derive from precipitation falling on the flanks Medicine Lake Volcano, but this theory awaits proof.

## A Hybrid Geomorphic Province

The region has the pattern of closely spaced faults typical of the Basin and Range province to the east, blanketed beneath volcanic rocks similar to the Cascade Range Province with towering Mount Shasta to the west. Linear northwest-trending uplands, such as the Whitehorse Mountains, and broad fault-controlled basins, such as Fall River Valley, express Basin and Range structure. This region is part of the multi-component boundary between the North American and Pacific tectonic plates.

## Final Thoughts

The rocks and landforms created by molten lava spewing from the depths of the earth now collect the cold precipitation that falls from the sky. Processes from the inner earth and of the atmosphere unite in Ahjumawi Lava Springs State Park.

*Written by Michael Wopat, California Geological Survey*
*Photos: Michael Wopat*

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# Great Valley Geomorphic Province

The **Great Valley** is an alluvial plain, about 50 miles wide and 400 miles long, located between the Coast Ranges and the Sierra Nevada. It is drained by the Sacramento and San Joaquin Rivers, which join and enter San Francisco Bay. To the north, the Sacramento Valley floodplain is interrupted by the Sutter (Marysville) Buttes, an isolated Plio-Pleistocene volcanic plug about 2,000 feet high. The valley is filled with nearly flat-lying sediments as much as 20,000 to 40,000 feet thick. Beneath the valley, Cretaceous and Cenozoic strata form a broad U-shaped cross-sectional profile (trough) that is steeper on the west than the east. The edges of the tilted layers of Great Valley sedimentary rock can be seen along the western margin of the trough adjacent to the Coast Ranges. In the southern part of the Great Valley, the San Joaquin Valley oil fields follow uplifts and fault warps that formed “traps” for petroleum, such as those found in the Kettleman Hills.

The Great Valley has become one of the leading agricultural regions in the world due to a mild climate and extensive, fertile soils. These soils formed in wetlands as floodplain deposits replenished by sediment carried in the Sierran rivers during periodic, large floods. The floods and vast wetlands delayed the development of the Great Valley. To a large extent the floods and the sediment are now cut off by flood control and water storage dams.

## Tectonic Setting

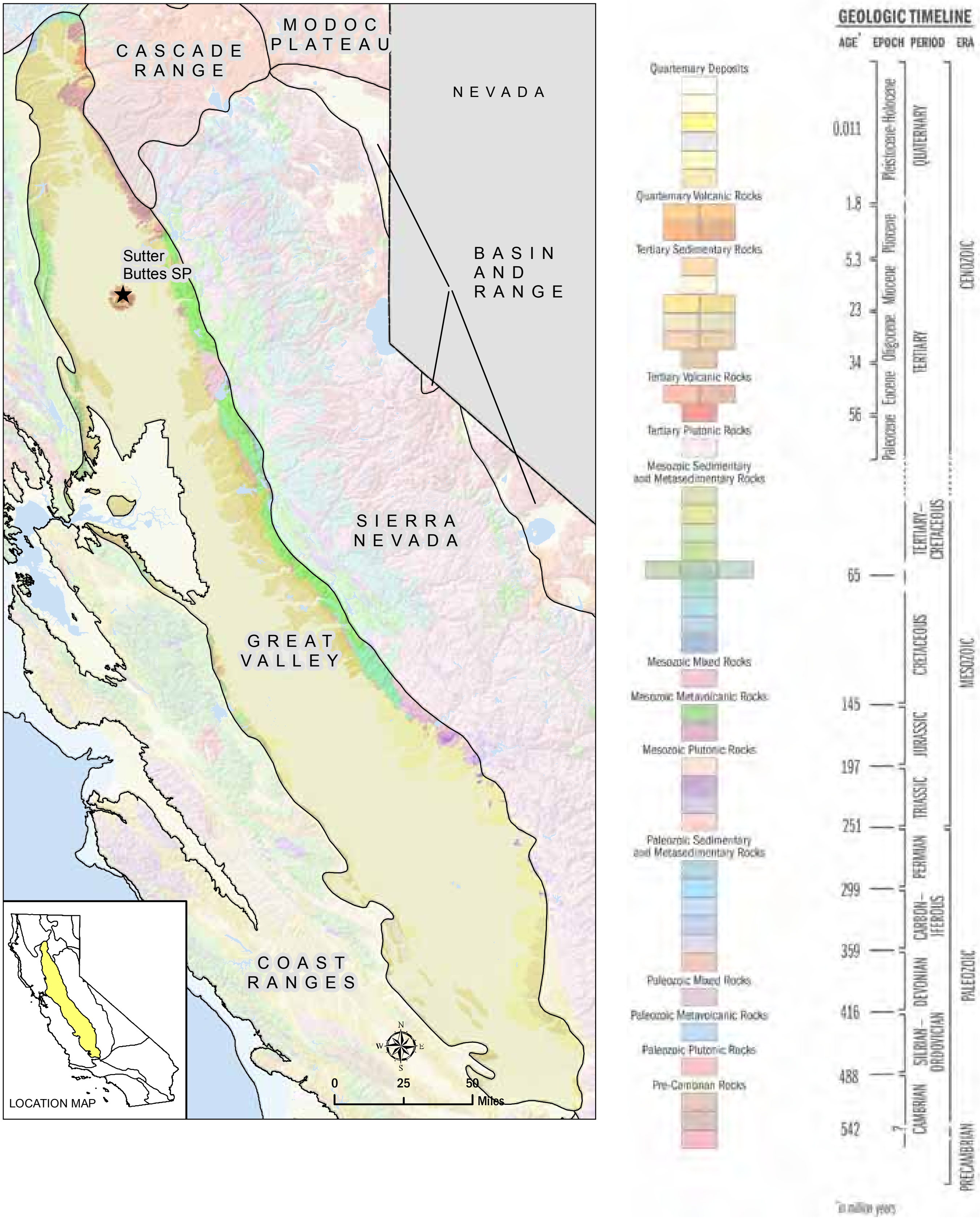
The trough is often interpreted as a fore-arc basin between the Sierra Nevada Mountains on the east and the accretionary wedge of the Coast Ranges on the west. Sediments eroded from the Sierra Nevada and the Coast Ranges were washed into the trough, at that time occupied by the sea. The shoreline ran along the eastern edge of the modern Great Valley where sediments were deposited in deltas at the mouths of Sierran rivers. These rivers carried the abundant outwash of the glacial erosion (as exemplified at Emerald Bay State Park) into the trough. The trough eventually filled with sediment and the seas retreated.

## GeoGem

**Sutter Buttes State Park** is the lone GeoGem representing the Great Valley. It is an anomaly that affords wonderful views of the Great Valley and the surrounding wetlands that are such an essential part of the Pacific Flyway. Along the flanks of the Sutter Buttes, the rock formations that underlie the Great Valley have been uplifted and tilted. Although the flat Great Valley lacks the dramatic topographic relief common to other geologic wonders, its expanse and proportion are unparalleled—the breadth and extent of the valley are evident from space, appearing as a broad planar feature, dissected by arrow-straight roads and patchworks of irrigated fields.

*Written by Mike Fuller and others, California Geological Survey*
*Photos: Mike Fuller*

## Simplified Geologic Map | Great Valley Geomorphic Province



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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 29

# Sutter Buttes State Park

## An Isolated Occurrence?

The Sutter Buttes' pristine shape has not been greatly modified by glaciers, subsequent eruptions, massive landslides, or earthquakes. In California, other volcanoes belong to chains or aligned clusters, such as: 1) the Cascade Range, 2) clusters in the Coast Ranges, or 3) along highly deformed rift zones along the eastern edge of the Sierra Nevada. In contrast, the Sutter Buttes volcano is isolated far from other volcanic activity. The origin of the Sutter Buttes has puzzled generations of scientists. At first glance, the buttes seem to align with the great Cascade volcanic chain that includes Mounts Shasta and Lassen; however, that chain actually swings eastward into the Sierra Nevada. The age of the volcanic rocks that make up the buttes more closely corresponds with the northern volcanic fields in the Coast Ranges (the closest of which is to the west at Mount Konocti towering over Clear Lake State Park); but the Sutter Buttes are way off that track—an outlier.

**Features:**

Volcanic geomorphology of an oddity

## Volcanic Domes

From a distance, the Buttes tower above the flat valley floor rising above the plain like a castle, surrounded by a moat, and built upon a mound or rampart. Ancient landslide deposits mantle the lower slopes of the domes. Along the perimeter of the Buttes,

**Why it's important:** The Sutter Buttes are the remains of a period of violently active volcanic eruptions between 1.35 and 1.6 million years ago. The origin of the Sutter Buttes has been hotly debated. The volcanic activity has been variously related to the Cascade Range to the North, to the Sonoma volcanics to the south and west, and to plate tectonic interactions deep below the terrestrial crust.

the generally flat-lying sedimentary rocks of the valley were upturned by the upward movement of molten lava from below. Most of the upturned sedimentary rock has been subsequently buried beneath an apron of debris and ash deposits; but where exposed to erosion, the sedimentary rocks erode faster than the harder volcanic rock—leaving a circular trough that resembles a moat. The geologic map of the Sutter Buttes looks like a ten mile diameter dart-board. The bull's eye (one-half mile across) consists of deposits of an extinct lake that occupied the center of a broad (three-mile diameter) volcanic dome. Surrounding the dome is a narrow (less than one-quarter mile wide) circular trench (moat) partially occupied by a dozen or more small domes. This ring is surrounded by a broader (2.5-mile-wide) outer ring of ash and debris flow deposits (rampart). Beyond the outer ring are the generally flat-lying sedimentary rocks of the Sacramento Valley.

**The origin of the Buttes has puzzled generations of scientists.**

The state park occupies the northeastern quadrant of the Buttes although it does not extend all the way from the central castellated core to the outer ramparts. Beautiful Peace Valley—the centerpiece of the state park—lies within the trough (moat), walled in by steep volcanic domes. In one small outcrop, on Cemetery Hill, the vertically upturned sandstone beds of the valley floor are exposed. Adjacent to the park, North Butte towers over Peace Valley.

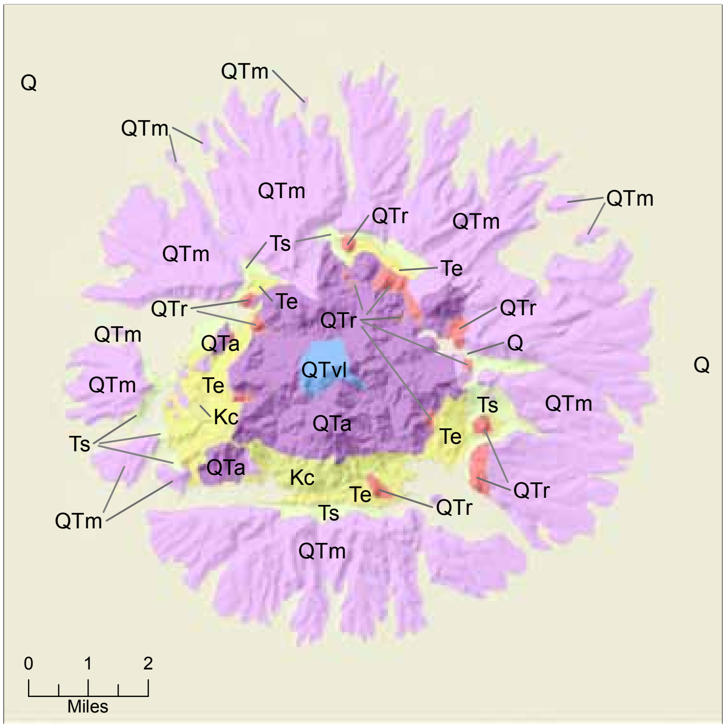
**What you can see:** Within and surrounding the park are volcanic domes and flows situated anomalously in the center of the Great Valley Geomorphic Province. Peace Valley is an elongate interior valley surrounded by layered accumulations of volcanic flows, ash, and debris.

## Landscape Formation

From about 2.5 to 1.4 million years ago, the Sutter Buttes developed as a series of small molten bodies of magma that rose like thick, hot toothpaste through one mile of sedimentary rocks to protrude above the valley floor surface. The molten bodies cooled significantly and mostly crystallized as they ascended. Near the intrusions, the flat-lying sedimentary blanket was tilted to near-vertical as the hot blobs rose. Some molten rock erupted onto the surface leaving hot ash and debris deposits that tilt valley-ward. Chemically, the magma bodies were of two distinct compositions that formed different rock types—andesite and rhyolite. Abundant, glassy quartz crystals in the rhyolite distinguish it from the andesite. Andesite forms the main central dome; while rhyolite forms most of the smaller domes encircling it. How and why two distinctly different magmas extruded to create the Buttes remains a mystery.

Over the roughly 1 million year period of formation and the subsequent 1.4 million years, the forces of erosion have been at work. During the early history of the Buttes, the climate was much wetter as glaciers advanced in the Sierra Nevada and Cascade Ranges. Although the Buttes are high enough to receive snow, there is no evidence of glaciers having been in the Buttes. Episodes of torrential rain washed the ash and debris onto the sloping flanks (rampart) of the Buttes.

## Geological Relief Map of Sutter Buttes



**Lithology**

- 🟨 Kc, Cretaceous marine deposits
- ⬜ Q, Quaternary sediments
- 🟪 QTa, Andesite and dacite domes
- 🟪 QTm, Rhyolite ramparts
- 🟥 QTr, Rhyolite domes
- 🟦 QTvl, Lake bed deposits
- 🟨 Te, Landslide deposits
- 🟩 Ts, Tertiary marine and river deposits

Original mapping from Williams and Curtis (1977), and Thamer (1961). New mapping by Brian Hausback. Modified from USGS Fact Sheet 2011-3024, March 2011.

During the earlier period of volcanic activity, the landscape and drainage system was in a state of change. Landslides tumbled off the newly prominent peaks during this period. Old landslide deposits mantle the base of the domes with low-lying hills, peppered with slabs and blocks of rock. An acidic lake at the center of the Buttes received copious volcanic debris and eroded sediments. Eventually, the slopes stabilized and the current radial drainage pattern developed taking water away from the center of the Buttes and toward the Great Valley. Like the volcanism, the central lake is now long extinct. Remnants of the hardened lake deposits (approximately 1,000 feet of re-worked volcanic tuff and ash) have been mapped at the center of the bull's-eye.

## Final Thoughts

The modern topography evolved as erosion etched the assemblage of volcanic and sedimentary rocks. The older, weaker sedimentary rocks (sandstone and shale) weathered and eroded quicker than the surrounding new volcanic rock which stands out in sharp relief.

*Written by Mike Fuller, California Geological Survey*
*Photos: Mike Fuller*

Geological Gems of California State Parks, Special Report 230 – Fuller, M., Brown, S., Wills, C. and Short, W., editors, 2015 Geological Gems of California, California Geological Survey under Interagency Agreement C01718011 with California State Parks.

# Sierra Nevada Geomorphic Province

The Sierra Nevada is a tilted fault block nearly 400 miles long. Its east face is a high, rugged fault scarp that contrasts sharply with its gentle western slope. The massive granites of the higher elevations are modified by glacial sculpting, forming such scenic features as Yosemite Valley. Many west-flowing rivers cut deeply into the western slope. The high crest of the range culminates in Mt. Whitney with an elevation of 14,495 feet above sea level. The older metamorphic bedrock, in places still partly capped by much younger Tertiary volcanic rocks, contains gold-bearing veins associated with the northwest-trending Mother Lode.

## Tectonic Setting

The Sierra Nevada foothills, source of California's famous gold deposits, consist of ancient accreted terranes and one or more former subduction zones. The subduction zone(s) operated during the Mesozoic Era, 140 to 180 million years ago. The former Farallon oceanic tectonic plate was driven beneath the present day Sierra where it

melted into large molten bodies known as batholiths and plutons. The terranes and sediments that accumulated in the subduction zone of this former plate boundary have been metamorphosed by the heat and fluids that radiated off the molten batholiths and plutons that eventually cooled to become the Sierran granitic rocks.

Over the last five million years, faults developed along the eastern margin of the Sierra Nevada along which the range has risen to tower above the Basin and Range province to the east. Active faults and hot springs (characteristic of the Basin and Range) penetrate the Sierran monolith and demonstrate that the boundary zone is still evolving.

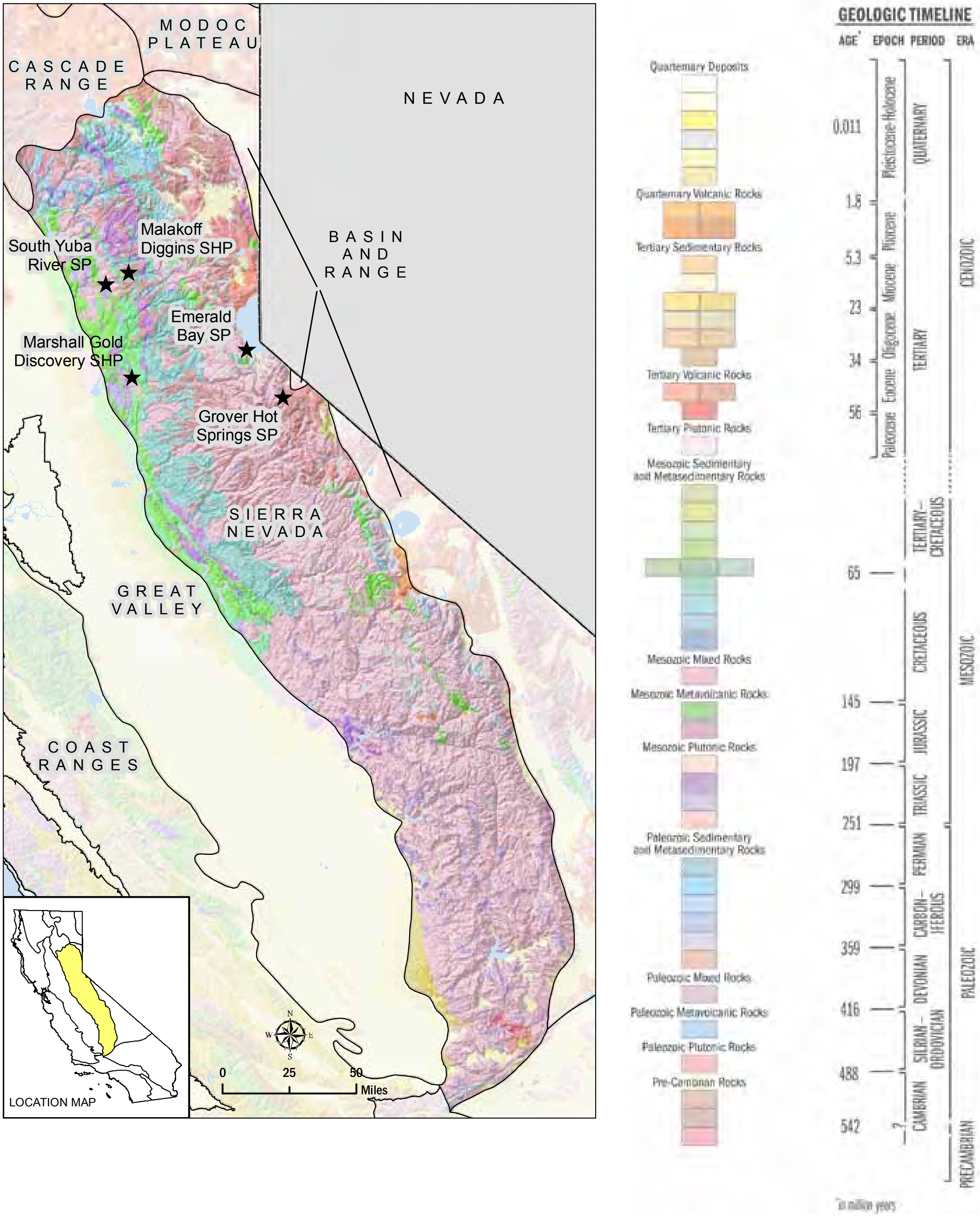
The uplift of the Sierra Nevada changed the climate in California and Nevada. The mountains became a barrier to storms originating in the Pacific Ocean that moved eastward over the land. In effect, California became wetter at the expense of Nevada. This increased precipitation allowed glaciers to cover the high Sierra during the Ice Ages of the past 100,000 years. The high Sierra parks (Emerald Bay State Park and Grover Hot Springs State Park) owe some of their majestic beauty to the effects of long gone glaciers.

## GeoGems

**Malakoff Diggins State Historic Park, South Yuba River State Park,** and **Marshall Gold Discovery State Historic Park** represent the Sierra foothills while **Emerald Bay State Park** and **Grover Hot Springs State Park** represent the exceptionally scenic eastern escarpment of the lofty Sierra. Emerald Bay State Park and Grover Hot Springs State Park lie along the current boundary with the Basin and Range geomorphic province.

*Written by Mike Fuller and others, California Geological Survey*
*Photos: Mike Fuller*

## Simplified Geologic Map | Sierra Nevada Geomorphic Province



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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 31

# Malakoff Diggins State Historic Park

## The Ancient Sierra Nevada

Between 65 and 34 million years ago, the ancestral Yuba River flowed down a much different course than today. The ancient river course has been inferred using remnant gravel deposits. The ancestral Yuba River was much larger than today, with a broad floodplain and thick gravel deposits between undulating hills. The river's grade was gentler than at present (up to 17 feet drop per mile, compared to today's average grades of up to 150 feet drop per mile). The white gold-bearing (auriferous) gravels in the lower half of the bluff were deposited during this time.

**Features:**

Archeology and paleo-geomorphology of paleo-placer gold, and auriferous gravels

**Processes:**

Erosion, deposition, tectonics

## A Temperate Time

Besides gold, the auriferous gravels also contain an extensive array of plant and vertebrate fossils. Plant fossils indicate that during the time when the auriferous gravels were being deposited, the climate was mild—temperate to subtropical. The mean annual temperature was probably between 10 and 15 degrees Fahrenheit warmer than at present. Animal fossils include ancestors of the horse and camel, and turtles.

## The Landscape Turned Upside-Down

Thirty-four million years ago marked the onset of volcanic activity in western Nevada. Volcanic eruptions associated with crustal extension in the Basin and Range geomorphic province filled the channels of the ancestral Yuba River with volcanic ash flows and lava flows. The volcanic flows buried and preserved the gravels by forming an erosion-resistant volcanic layer.

The brown or tan colored gravels in the upper half of the bluffs at Malakoff were deposited shortly before and during this period. The brown color comes from the volcanic rocks and detritus contained within these gravels.

The filling of the river valleys with volcanic mud flows diverted the streams, which began cutting new channels. As the Sierra Nevada once again began to rise, these new river channels were incised and the ancestral channels became perched on ridge tops, a characteristic known as inverted topography, i.e. the ancient valley bottoms are now the ridge tops.

## Origin of the Gold

Gold-bearing rocks were first formed around hydrothermal vents on the sea floor at oceanic volcanic ridges. These deep-ocean gold-bearing crustal rocks were incorporated (accreted) onto the North American continent by plate tectonics. The

**Why it's important:** From a geologic perspective, the ancient river gravels are important in that they provide insight into the timing of the geologic events that gave rise to the current Sierra Nevada. From the human perspective, the gold in the gravels was a source of vast wealth that drove the development of early California.

**What you can see:** Near-vertical cliffs created by hydraulic mining of two different generations of ancestral Yuba River gravels demarcated by their white and brown colors, plant and animal fossils, differential erosion (waterfall), ground sluices, and a mine drain tunnel.

accreted ocean floor rocks were later intruded by the granitic magma (molten rock) of the Sierra Nevada. Super-heated fluids associated with the granitic intrusion dissolved, mobilized, and concentrated the gold into milky white quartz veins. The rocks containing the quartz veins and gold were weathered and eroded, liberating the gold and creating the white auriferous gravels.

## Extracting the Gold from the Gravel

The hydraulic mining that created Malakoff Diggins was not the first method used to mine the auriferous gravels. Initially, the ancient gravel deposits were mined by tunneling, just like hard-rock mining. Miners soon discovered that the gold was concentrated at the bottom of the ancient river channels, just as in modern streams. They would sink a shaft until they hit the ancient bedrock that formed the bottom of the river channel and then tunnel along the channel bottom, scouring the bedrock.

Hydraulic mining was possible after a network of water diversions and ditches was constructed. Then, miners used huge water cannons called “monitors” to wash whole hillsides down into sluice boxes where the gold was recovered. The sluice boxes were embedded at the lowest level of the hydraulic pit, thus the name “ground sluice.”

As hydraulic mining progressed, the workings became a pit. Managing the sediment and water became a messy problem as the pit filled with water and mud. This problem was solved by excavating a drain tunnel through the bedrock below the gravels, and draining the pit to Humbug Creek at a lower elevation.

Drain tunnels were used at all the hydraulic mines not just at Malakoff. These mines dumped several cubic miles of sediment and debris into the Yuba and other rivers, aggrading (filling up) the channels and causing widespread flooding in the Sacramento Valley. The devastation from the flooding led to the creation of California’s first environmental law, the Sawyer Decision in 1884, which prohibited discharging mine debris into streams and rivers.

## Final Thoughts

The pursuit of gold stimulated technological engineering and societal advances. The legacy of mineral recovery effects lingers, and Malakoff Diggins State Historic Park serves as a protected outdoor classroom or laboratory to better understand mining effects and ecological recovery.

*Written by Stephen Reynolds, California Geological Survey*
*Photos: Mike Fuller*

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# South Yuba River State Park

## Local Gold Mining History

**Feature/Process:**

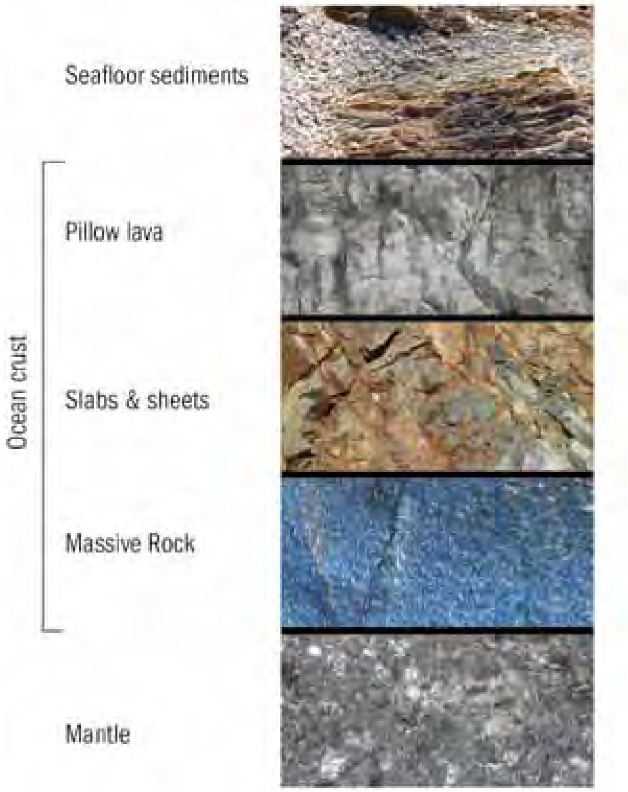
Exotic terranes along an ancient plate boundary in the Sierra

The Yuba River area became famous during the Gold Rush as being exceptionally rich in gold. The nearby Grass Valley gold district was the richest and most famous gold district in California. Gold was found within quartz veins that cut across various metamorphic and granitic rocks such as are revealed in the park. The gold deposits that were eroded by the river became a second type of deposit, placer deposits in the river channel—like those found near Coloma in Marshall Gold Discovery State Historic Park. The ancestral course of the Yuba River was quite different than today. It also contained placer deposits. Starting about 34 million years ago, huge volcanic flows of ash, mud, and rock from the east filled the canyons, buried those placers, and caused the river to change course. Gradually, a new canyon formed through the volcanic cap rock, into the ancient gravels, and deeper into the bedrock. The gold-bearing gravels of the ancestral river were discovered up the canyon walls and along ridges, making them a third type of deposit. Those deposits were mined in two basic ways. First, miners excavated the gold bearing gravels directly out of the slopes, and when necessary, they cut tunnels (drifts) into the hillside following the ancient river course. Next, they dug pits, big pits. With the development of hydraulic mining, enormous pits were excavated. Nearby Malakoff Diggins State Historic Park is an excellent example. Of course, such large-scale mining (in the days before environmental damage was considered) had enormous consequences that spawned some of California's first environmental rules. With three types of gold deposits, it is no wonder the Yuba River area and the Grass Valley district were such a treasure trove.

## Sea Floor, then Sierra Nevada Foothills

The South Yuba River cuts through three different major rock types: ophiolite, granitic plutons, and metamorphosed volcanic sedimentary rocks. Within the park, the scenic river canyon provides a deep, 20-mile-long cross-section of the ancient oceanic-continental tectonic plate boundary, which reveals the "roots" of the modern Sierra Nevada. Each major rock type is completely bounded by ancient faults. The majority of the faults run generally north-south dividing the rocks into parallel strips or "belts." The rocks are part of the Foothill metamorphic belt, which extends over a hundred miles along the foothills of the Sierra Nevada and includes the famous Mother Lode Gold Belt and the West Gold Belt. This amalgamation of different rocks is collectively called the Foothill Terrane, a term that refers to the oceanic origin and subsequent accretion of these rocks to the edge of the North American tectonic plate.

Rocks of the Smartville ophiolite (~152 to 164 million years old) crop out near Bridgeport in the western portion of the park and represent oceanic crust. They are bounded by the Grass Valley Fault on the east where they abut the granitic rocks. The ophiolite within the park consists mostly of gabbro (a dark igneous rock similar to granite in texture), and metavolcanics. The landscape underlain by gabbro consists of rolling hills with dark red soils covered by oak woodland and grasslands. Rice's Crossing downstream of Bridgeport is a good location to view the rocks of the ophiolite.



**Ophiolite:** A layered assemblage of rocks that formed as a section of oceanic crust. The crust forms at rifts in the oceanic crust producing a characteristic sequence of layers. The rate of cooling of molten rock is controlled by the depth below the ocean floor where water quenches the rock. The deeper layers are cooled more slowly while the uppermost layers cool rapidly. Pillow basalts typify the upper layers, while intermediate layers develop as vertical slabs and lowermost layers develop as massive rock.

**Why it's important:** Once the South Yuba River watershed was the focal point of the California Gold Rush. Today, it is recognized by the California State legislature as a Wild and Scenic River with scenery of "Outstandingly Remarkable Value." This park which follows the river for twenty miles provides a very scenic geologic cross-section of a part of the state that played prominent roles both geologically and economically in California's history.

Green serpentinite, the State rock marks the boundary (Grass Valley Fault) between the ophiolite and the granitic rocks. Serpentinite produces a soil toxic to most plants, including oaks; as a result, vegetation overlying the serpentinite is sparse and soils are thin. The Highway 49 bridge provides a good access point to view this boundary area.

The granitic rocks comprise the Yuba Rivers pluton—a mass of rock that crystallized deep in the earth about 154 to 160 million years ago. These rocks produce distinctive landforms and soils. The soils are generally tan to whitish color, but can be reddish in some places. The canyon cut through the pluton and is characterized by steep slopes and an incised bedrock channel. Many giant boulders line the channel. Purdon Crossing is a good vantage point to see the rocks of the Yuba Rivers pluton, one of many plutons that intruded the accreted metamorphic rocks to build the bulk of what is the Sierra Nevada.

**What you can see:** A steep canyon traversing the ancient oceanic-continental tectonic plate boundary, which reveals the “roots” of the modern Sierra Nevada.

On the east side of the park, these rocks abut metamorphic rocks of seafloor origins. The metamorphic rocks extend another six miles east of the park boundary to the Melones Fault and the serpentinite rock that marks the fault zone. This fault crosses through the area at the town of Washington, and marks the northern projection of what was referred to as the Mother Lode during the Gold Rush.

Between the Yuba Rivers pluton and the Melones Fault, the metamorphic rocks (called greenstone) are dark colored, sometimes almost black. The bridge at Edwards Crossing is a good access point to see these metamorphic rocks. Depending on the degree of metamorphism, some rocks retain relict textures that allow recognition of the original rock type. Metamorphism included the re-crystallization of elongate minerals along parallel planes, giving the rock a “foliation” and a tabular appearance in outcrop. The foliation is generally aligned north-south and gives the landscape a distinctive “grain.” The river course through these rocks zigzags as it follows the foliation for a distance, then is forced to cut across it. The canyon walls are steeper in this section than in the granitic section. The river bed is primarily bedrock with occasional deposits of cobbles and boulders. At the Ramshorn Fault at the east end of the park near Missouri Bar, the rocks change to thin or platy yellowish slates of the much older Calaveras Complex.

## Final Thoughts

Like a surgeon, the South Yuba River cut an incision across the earth’s surface to expose the inner anatomy of the Sierra Nevada.

*Written by Mike Fuller, California Geological Survey*
*Photos: Mike Fuller*

Geological Gems of California State Parks, Special Report 230 – Fuller, M., Brown, S., Wills, C. and Short, W., editors, 2015 Geological Gems of California, California Geological Survey under Interagency Agreement C01718011 with California State Parks.

# Marshall Gold Discovery State Historic Park

## Why Was There Gold at Sutter's Mill?

**Feature/ Processes:**
Archeology, geology and hydrology of modern placer gold, and the "gold rush" discovery site

The gold found at Sutter's mill site at Marshall Gold Discovery State Historic Park occurred in the sands and gravels of the South Fork of the American River and in stream terrace gravels along the river bank. Concentrations of gold in sand and gravels along rivers and streams, like those at Sutter's mill, are called placer gold deposits. The term "placer" was probably first used by early Spanish miners in both North and South America to refer to gold deposits in sands and gravels of streams. Originally the term meant "sand bank" or "a place in a stream where gold was deposited."

Gold particles have a high density (high weight per volume) compared to water and to most other minerals and rocks. Gold is seven times heavier than quartz—the main constituent of sand. As a consequence, gold particles require faster moving water to be carried or pushed along in streams and rivers than do particles of other minerals and rocks. This density difference causes gold to concentrate in places where the water speed changes from fast to slow. When the water flow decreases gold drops out sooner than most other sediment particles. Examples of places where water flow slows and gold may accumulate are: along the inside bends of streams or rivers; where eddies (areas of circular water movement to the side of the main current) are present in the water; in small areas behind boulders; at the heads of quiet pools; and behind irregularities (natural riffles) on the bottom of stream or river channels. Gold deposited at these locations usually resides in place. During storms with extremely high rainfall or periods of flooding, gold particles may be transported downstream to new locations. If gold particles get buried by sediments, these sediments may prevent the gold from being moved further downstream during times of higher flow.

Photo: Public domain

### Why it's important:

Although small amounts of gold had been found in other parts of California, it was the gold discovery at Sutter's mill that received world-wide attention in 1848. The discovery caused one of the largest mass-migrations in history, bringing people to California from all over the world. Most prospectors who came did not strike it rich in the gold fields and returned home, but about ten percent stayed in California. Those who stayed contributed to California's rapid commercial, agricultural and industrial development, and hastened statehood in 1850. These developments prompted dramatic transportation improvements, the most important being the transcontinental railroad. Completed in 1869, it connected California to the eastern U.S. and helped raise the State's agricultural industry to national prominence. The discovery of gold at Sutter's mill started it all.

Most of the gold present in the placer deposit at Sutter's mill probably originated from within the Mother Lode gold belt. The river crosses this belt about five to seven miles upstream from the Sutter's mill site. The Mother Lode gold belt is about one-half mile to one mile in width and 120 miles in length; extending from Georgetown south through Placerville and on to Mariposa. It is associated with the Melones Fault system. Numerous underground gold mines were active for about 100 years along the Mother Lode gold belt.

The Mother Lode gold belt formed about 140 to 150 million years ago. At that time, the geologic setting of the Sierra Nevada was similar to the Andes in South America today. Ocean crust and continental sediments—sliding beneath the edge of the North American continent—were carried deep enough that they melted. The resulting magma (molten rock material) moved upward into older rocks along the edge of North America and solidified, miles below the surface, to form granite rock bodies called batholiths. These granite batholiths are exposed at the surface in many parts of the Sierra Nevada Mountains today. One underlies the sediments at Marshall Gold Discovery State Historic Park, and outcrops of this granite batholith can be seen in portions of the park today. During their final stages of crystallization, some of the fluids (associated with these granitic rocks) consisted of very hot water with dissolved

**What you can see:** Gold-bearing stream sediment along the South Fork of the American River in the Sierra Nevada foothills

silica, carbon dioxide and gold. These fluids moved into fractures in the older rocks along the Melones Fault zone and solidified, forming gold-bearing quartz veins. The fluids also deposited gold in the rocks along the edges of the fractures. The quartz vein formation and gold deposition occurred several miles below the surface of the ancestral Sierra Nevada, forming the Mother Lode gold belt.

**Concentrations of gold in sand and gravels … like those at Sutter's mill, are called placer gold deposits.**

After the Mother Lode gold deposits formed, there was a long period of uplift and erosion which eventually exposed these gold deposits at the earth's surface. Once at the surface, weathering and erosion processes freed gold from Mother Lode deposits and carried it into the streams and rivers that flowed southwestward off the Sierra Nevada. This gold accumulated and formed placer deposits in favorable places along these streams and rivers. Between 33 and 4 million years ago, several vast volcanic eruptions filled the existing stream and river channels with lava flows and ash, burying these placer gold deposits. New streams and river channels eventually formed in response to burial, renewed uplift, and westward tilting of the Sierra Nevada. These now westward flowing streams and rivers eroded through the volcanic cover to re-expose the buried placer gold deposits and the

Mother Lode gold belt. The present day South Fork of the American River was formed at this time. Its channel eroded deeply enough to intersect the Mother Lode gold belt and expose these gold deposits to renewed surface weathering and erosion. Once again, gold particles were being freed from host quartz veins and rocks but now they were being carried with other sediments down the South Fork of the American River. At favorable locations along the river, gold particles accumulated and formed new placer gold deposits, including one ultimately discovered by James Marshall in 1848.

## Final Thoughts

The park provides a sociological case study of how the distribution of earth's mineral resources has influenced the establishment and demographics of societies.

*Written by Ron Churchill, California Geological Survey*
*Photos: Mike Fuller (except where noted)*

Geological Gems of California State Parks, Special Report 230 – Fuller, M., Brown, S., Wills, C. and Short, W., editors, 2015 Geological Gems of California, California Geological Survey under Interagency Agreement C01718011 with California State Parks.

GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 34

# Emerald Bay State Park

National Natural Landmark 1969

## Why Glaciers Formed

The glacial history of the Tahoe basin is inextricably linked to the geologic structure and seismic history of the region. The Tahoe basin straddles the boundary of the Sierra Nevada geomorphic province and the Basin and Range geomorphic province. On the west side of Lake Tahoe, crustal movement along the Sierra Frontal Fault system is responsible for the steep fault escarpment that leads to the crest of the Sierra. Lake Tahoe occupies a deep basin created by cumulative descent along the faults. The faulting—related to the uplift of the Sierra Nevada and the extension of the Basin and Range—remains active today. As the Sierra Nevada was uplifted, it created an orographic effect on weather patterns, causing the Sierra to capture an excessively large share of regional precipitation.

### Features/Process:

Glacial geomorphology along a nascent plate boundary

The increased precipitation and the higher elevations combined to increase moisture and snow accumulation in the Sierra Nevada. The uplift and increased precipitation set the stage for multiple episodes of Sierran glaciations during the Pleistocene Epoch when global climate was much cooler. Glaciers fed by abundant snowfall formed on the elevated Sierran peaks and sculpted the valleys and lakes on the western slopes. On the east side of Lake Tahoe, the more rounded landforms of the Carson Range were not as sculpted by glaciers—being in the drier rain shadow.

## What the Glaciers Did

Glaciers plowed down canyons and then retreated during multiple (four to six) cycles of global warming and cooling (glacials and interglacials). Each glacial period may have lasted several thousand years. With each advance of the glaciers, evidence of previous lesser advances was obliterated. The two most recent glacials were the Tahoe Stage (~160,000 years ago) and the less extensive Tioga Stage (~20,000 years ago). The glaciers whittled away peaks, broadened canyons, and gouged lake basins. Rock was broken and pulverized into glacial till. The till was plowed and piled along the margins (lateral moraines) and front (terminal moraine—the "mouth" of Emerald Bay) of the glaciers.

During the Tahoe Stage, long fingers of ice descended stream valleys from the highest mountain peaks down toward Lake Tahoe. The subsequent Tioga Stage re-worked the glacial deposits, further scraped the landscape, deposited lateral and terminal moraines and formed the lake basins along the southwestern shore of Lake Tahoe.

Emerald Bay owes its origin to a four-mile long glacier that formed on the north slopes of Dicks Peak (elevation 9,974 feet), plowed its way down Eagle Creek, and probably extended into Lake Tahoe (elevation 6,229 feet). The lateral moraines flank the bay. During the more extensive Tahoe Stage, the glacier likely merged with another glacier emanating from Rockbound Valley at higher elevation in the Desolation Wilderness.

If the level of Lake Tahoe dropped just ten feet, Emerald Bay would become a separate lake, just like neighboring Fallen Leaf Lake and Cascade Lake. This may have

**Why it's important:** Emerald Bay is California State Park system's premier glacial park–owing its spectacular scenery and dramatic alpine peaks, ridges, and crystalline lake to the scouring action of glaciers that existed at various times during the Pleistocene Epoch (11,500 to 1,800,000 years ago). Glaciers as thick as several hundred feet buried all but the highest peaks of the Sierra and fingers of ice pushed down from the Sierran crest and gouged out stream canyons, scraped off soil and weathered rock, deposited moraines and carved out lake basins.

**What you can see:** Emerald Bay fills a large, oval depression gouged out by a series of glaciers and is surrounded by glacial deposits. Fannette Island is a glacial feature called a "roche moutonnée (translates to "sheep rock") due to a semblance of a grazing sheep. The shape was carved and abraded by the overriding glacier that left behind the resistant knob that is Fannette Island. Recent landsliding and vigorous stream erosion modify the surrounding steep terrain.

occurred during a prolonged dry period between 1750 and 1850 when lake levels were several feet lower as indicated by submerged stumps just below the lake shoreline. Even older stumps are found in deeper waters, 60 to 70 feet below the surface. These trees likely grew during a prolonged drought (~5,000 to 6,300 years ago), known as the Altithermal, a period that was warmer and drier than today. At that time Emerald Bay was most certainly a separate lake, if it wasn't dry.

## After the Glaciers

As the climate warmed, the glaciers gradually melted and retreated. The streams were vigorous, and full of meltwater and glacial sediments that washed into Lake Tahoe. Some of those sediments were deposited as a large delta off of Emerald Point. Over thousands of years, soils developed on the granitic valley slopes and conifer forests took root. The thin soils of decomposed granite on the slopes are very erodible.

The granitic (mostly granodiorite) bedrock exposed by the glaciers is evident throughout the area around Emerald Bay. The deposits of glacial till (a loose assortment of boulders, small rocks, and soil) form linear hills (moraines) that flank

the bay. The bedrock is fractured into great slabs which occasionally break loose from hillsides. This can be seen as piles of blocky rock at the base of slopes along Eagle Creek. The scars of large landslides that damaged the highway in 1955 and 1980 and avalanche chutes are evident in the park and remind us that the forces of nature are still at work shaping the landscape, albeit at a “glacial” pace.

## Final Thoughts

The glacial and post-glacial events experienced by this beautiful landscape provide powerfully instructive tools that can lead us to better understand the natural and wildly fluctuating climatic conditions that shape the land of today.

*Written by Mike Fuller, California Geological Survey*
*Photos: Mike Fuller*

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# Grover Hot Springs State Park

## Hot Springs and Geothermal Systems

**Process/Feature:**
Hydrogeology along a nascent plate boundary, hot springs

Hot springs can be associated with fault activity and with volcanic processes. The thermal springs at Grover Hot Springs State Park are thought to be related primarily to circulation of groundwater in connection with faulting, as water below the ground is heated by contact with abnormally hot rocks. The water carries dissolved minerals, depositing the minerals around hot springs and along the fractures that channel the waters to the surface. The contents of the heated water contain chemical clues to processes operative deep beneath the ground surface. The mineral deposits built up at Grover are carbonate, which precipitate at near-surface conditions as the lime-rich waters cool and reach normal surface pressures.

## Boundary Between Two Geomorphic Provinces

Sweeping vistas from high alpine zones to the desert below are the result of uplift of the Sierra Nevada along a major system of faults.

On a gross scale, the Sierra Nevada is a nearly intact block of igneous and metamorphic rocks that has been uplifted and tilted to the west. The boundary between the Sierra Nevada and the Basin and Range geomorphic province to the east is marked by a major zone of faults known as the Sierra Frontal fault system. The faults allow the Sierra crest to rise, while the blocks to the east drop and stretch. The Basin and Range is actually growing as the North American continent stretches and rifts due to plate tectonics.

**Why it's important:** Grover Hot Springs is treasured for its beautiful alpine setting and alleged restorative and refreshing natural hot springs. For more than 100 years nature lovers have been drawn to the springs to bask in the warm mineral waters and absorb the pleasant views of the tranquil peaks surrounding the hot springs meadow.

Grover Hot Springs shares its origin with numerous other hot springs that occur along the east side of the Sierra Nevada along the boundary with the Basin and Range geomorphic province to the east.

## Faults and Hot Springs

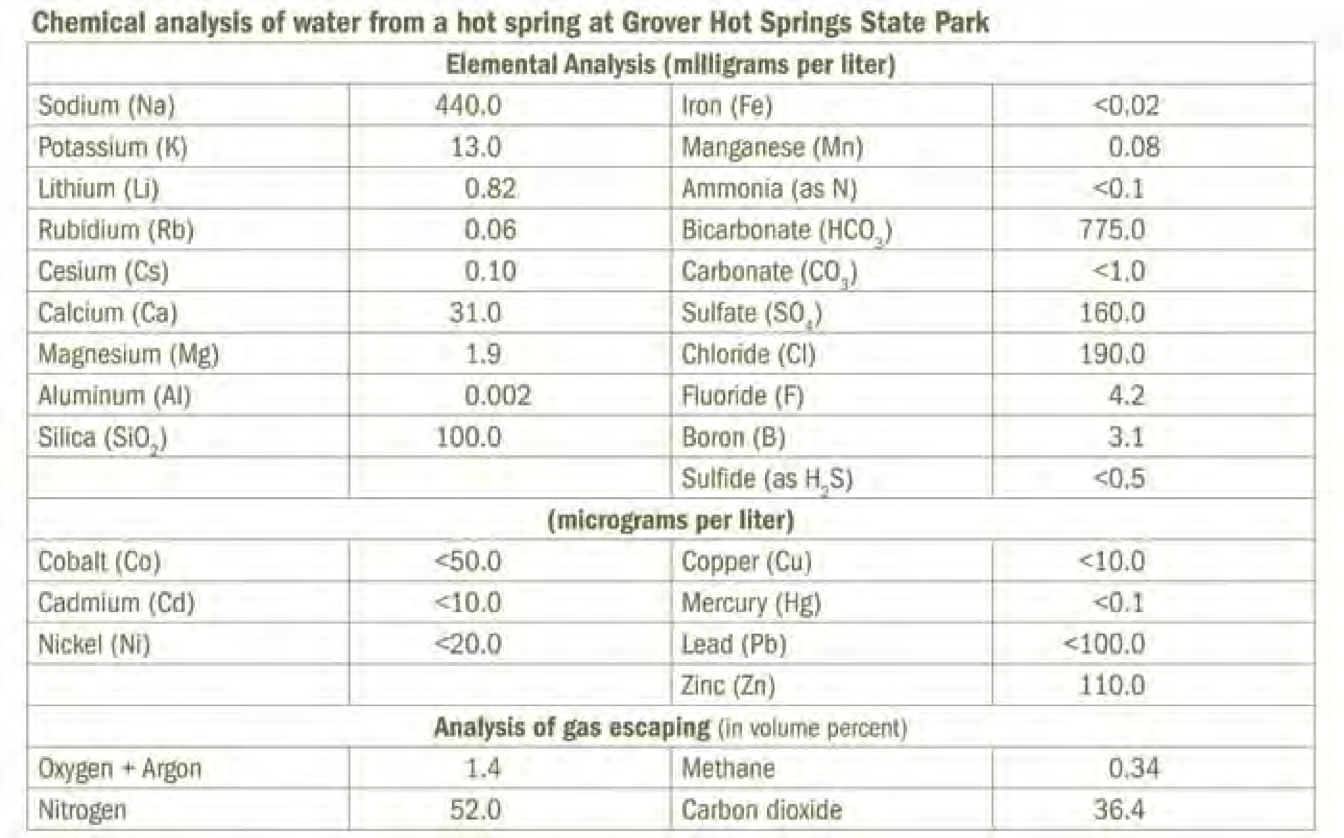
One strand of the Sierra Frontal fault zone, the Genoa Fault, follows the base of the mountain front south from Genoa, Nevada then extends into the mountains near the Grover Hot Springs. This fault is active, clearly offsetting young geologic deposits (younger than the last ice age). Studies near Genoa show the fault was active as recently as 300 years ago. A splay of the Genoa Fault helped form the valley in which the park resides and is probably the conduit for the rising hot water that emanates at the hot springs. The valley was also sculpted by glaciers that occupied it perhaps as recently as 11,000 years ago, and remnants of glacial moraines dot the landscape.

In general, rain and snowmelt seep down along faults to reach relatively shallow hot rocks; the water is heated and propelled upward to the surface before cooling.

## Chemistry of the Water

Prior to early commercial development, there were a dozen springs and seeps in two marshy areas about 100 yards apart, at the edge of the meadow on the southern side of Hot Springs Creek. The spring water is slightly acidic, gas-charged, and rich in sodium bicarbonate. Upon evaporation, it leaves a whitish crust at the surface which in areas has built up mounds and terraces of travertine (limestone). In the early 1900s, the hot and cold springs were developed to provide temperatures favorable to bathing by mixing hot and cooler water. The hottest spring varies from 128 to 146° F, depending on the contributions from rain and snowmelt.

**The content of the heated water holds chemical clues to processes operative deep beneath the ground surface.**



**Chemical analysis of water from a hot spring at Grover Hot Springs State Park**

| | | | |
|---|---|---|---|
| **Elemental Analysis (milligrams per liter)** | | | |
| Sodium (Na) | 440.0 | Iron (Fe) | <0.02 |
| Potassium (K) | 13.0 | Manganese (Mn) | 0.08 |
| Lithium (Li) | 0.82 | Ammonia (as N) | <0.1 |
| Rubidium (Rb) | 0.06 | Bicarbonate ($HCO_3$) | 775.0 |
| Cesium (Cs) | 0.10 | Carbonate ($CO_3$) | <1.0 |
| Calcium (Ca) | 31.0 | Sulfate ($SO_4$) | 160.0 |
| Magnesium (Mg) | 1.9 | Chloride (Cl) | 190.0 |
| Aluminum (Al) | 0.002 | Fluoride (F) | 4.2 |
| Silica ($SiO_2$) | 100.0 | Boron (B) | 3.1 |
| | | Sulfide (as $H_2S$) | <0.5 |
| **(micrograms per liter)** | | | |
| Cobalt (Co) | <50.0 | Copper (Cu) | <10.0 |
| Cadmium (Cd) | <10.0 | Mercury (Hg) | <0.1 |
| Nickel (Ni) | <20.0 | Lead (Pb) | <100.0 |
| | | Zinc (Zn) | 110.0 |
| **Analysis of gas escaping** (in volume percent) | | | |
| Oxygen + Argon | 1.4 | Methane | 0.34 |
| Nitrogen | 52.0 | Carbon dioxide | 36.4 |

**What you can see:** Hot springs emerging from a frontal scarp of the Sierra Nevada, fault bounded valley, granitic basement rocks with volcanic cap rocks and glacially-influenced landscape.

## Final Thoughts

The geologic history surrounding the park exemplifies the geologic development of the eastern Sierra Nevada geomorphic province.

*Written by Mike Fuller, California Geological Survey*
*Photos: Mike Fuller*

Geological Gems of California State Parks, Special Report 230 – Fuller, M., Brown, S., Wills, C. and Short, W., editors, 2015 Geological Gems of California, California Geological Survey under Interagency Agreement C01718011 with California State Parks.

# Basin and Range Geomorphic Province

Photo: Mike Fuller

The Basin and Range geomorphic province is characterized by subparallel, fault-bounded mountain ranges separated by down-dropped basins. Death Valley, the lowest area in the United States, is one of these down-dropped basins. Badwater, the lowest point in Death Valley, lies at 280 feet below sea level. In general, most of the valleys in the Basin and Range are actually elevated, with valley floors lying at more than 3,000 feet above sea level. The northernmost portion of the Basin and Range geomorphic province in California includes the Honey Lake Basin. The Basin and Range province is the westernmost part of the much larger Great Basin that extends across several states. The region is characterized by interior drainage with lakes and playas.

*Photos: Will Harris (left), Mike Fuller (center and right)*

## Tectonic Setting

The basin and range landscape forms in response to crustal thinning and extension (stretching and pulling apart from deep dynamic forces). California lies along the western edge of the province. For the last 40 million years, the Basin and Range has been stretching from east to west, resulting in tilt block mountains and intervening down-dropped basins. The State of Nevada is actually growing in area as a result of these extensional processes.

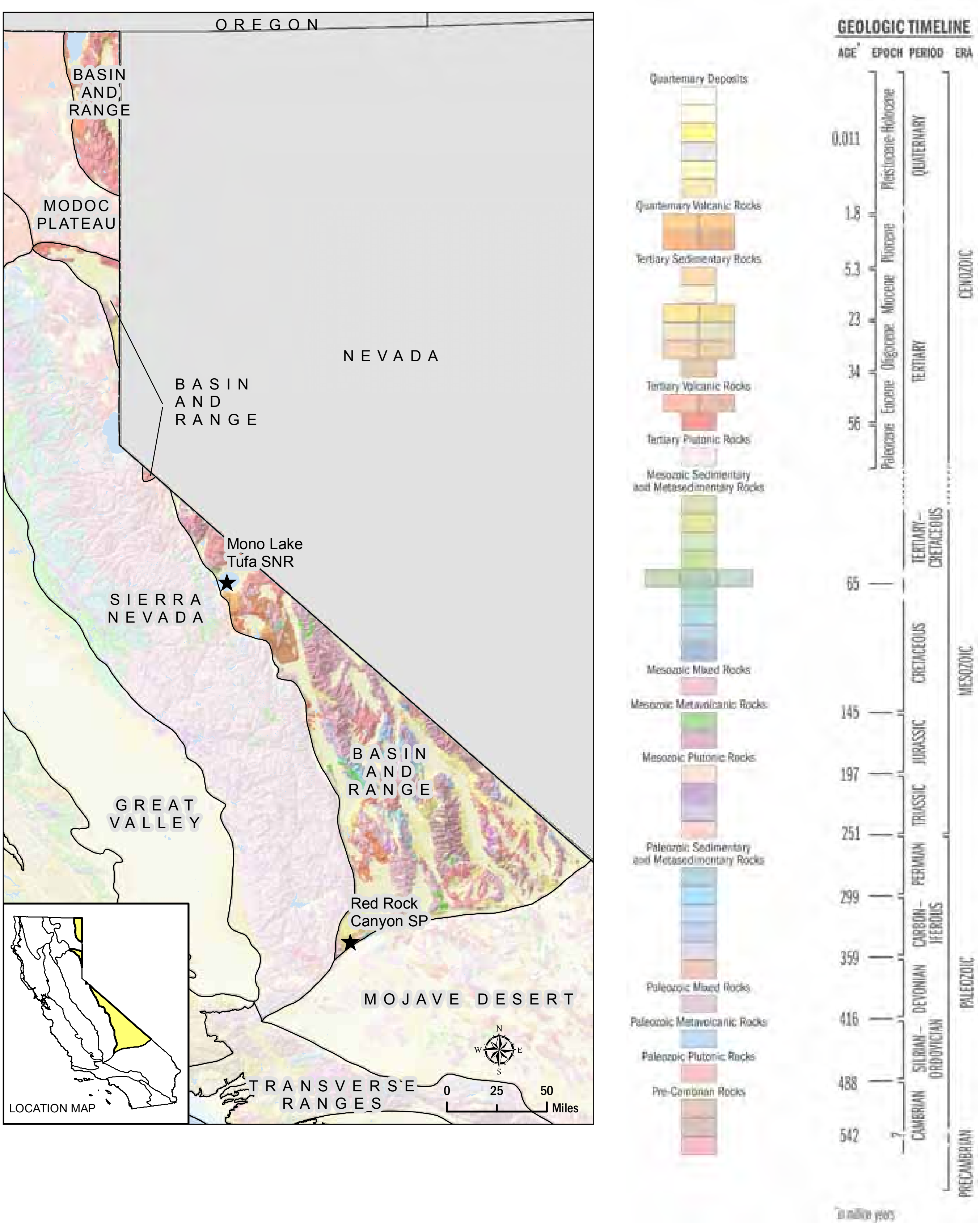
## GeoGems

**Mono Lake Tufa State Natural Reserve** and **Red Rock Canyon State Park** are the GeoGems that represent the Basin and Range. Both are located along the boundary with the Sierra Nevada. Mono Lake sits in the westernmost basin of the province below the eastern escarpment of the Sierra Nevada, essentially the westernmost range of the province–although treated as a distinct province. Recent earthquakes show this a very active boundary as the Basin and Range extension moves westward.

Red Rock Canyon lies near the boundaries of two other geomorphic provinces: Sierra Nevada and Mojave Desert. The early history of the Basin and Range province is revealed at Red Rock Canyon State Park. About 20 million years ago, roughly coincident with the birth of the San Andreas Fault system, the Basin and Range began to form. The sediments that deposited in one of the early basins now form the colorful cliffs in Red Rock Canyon.

*Written by Mike Fuller and others, California Geological Survey*

## Simplified Geologic Map | Basin and Range Geomorphic Province



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**Prepared by California Geological Survey, Department of Conservation | www.conservation.ca.gov/cgs**
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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 37

# Mono Lake Tufa State Natural Reserve

## Mono Lake and Mono Basin

**Features/Processes:**
Geochemistry of a desert lake, and saline "statues"

Mono Lake is one of the most unusual lakes in the world. Situated against the towering eastern front of the Sierra Nevada, the lake is at the boundary between the Sierra Nevada and Great Basin geomorphic provinces. Based on study of sediments that underlie the lake, geologists believe it is at least 760,000 years old and may be one or two million years old. In 2008, its salinity was about twice that of the ocean. The main causes of this unusually high salinity are the age of the lake (i.e. very long period of evaporation), its lack of an outlet to carry away dissolved salts from the contributing sediments, and the diversion of some of its freshwater sources to supply water demand in southern California, which began in 1941. The lake water contains large amounts of bicarbonate, sodium, chloride, and sulfate. The water is extremely alkaline (pH = 10), which makes it caustic.

**What you can see:** Mono Lake is an ancient saline lake whose recent history has been significantly affected by man's activities. Within the lake and along its shore are bizarre tufa formations. These have formed by springs reacting with the highly mineralized and concentrated, salty water of Mono Lake. North, east, and south of the lake are volcanic mountains. To the west is the dramatic fault scarp of the Sierra Nevada.

Mono Lake is contained within a large, shallow depression called Mono Basin. The basin probably began to form 3–4 million years ago, mainly by subsidence of the basin floor possibly due to volcanic eruptions and subsequent chamber collapses. As Mono Basin formed, creeks and springs flowed into it to create Lake Russell. Mono Lake is but a small remnant of this ancient lake. Abundant freshwater springs, some of them hot, are still active in the basin. Rising abruptly at the western edge of Mono Basin is the Sierra Nevada. At the foot of the range, a large fault, the Sierra Nevada Frontal Fault, is present, along which the Sierra Nevada has risen and Mono Basin has fallen. The maximum difference in elevation between the crest of the range and the basin floor is about 7,000 feet.

Panum Crater, south of Mono Lake and south of the park boundary, erupted explosively as recently as about 650 years ago. The volcanic mountains on the north and east sides of the basin are much older and more eroded.

## Tufa Formations

Two types of bizarre natural features rise from Mono Lake and its shoreline. These are the “tufa towers” and “related sand structures,” which are the geologic highlights of the Natural Reserve, and the basis for protective legislation establishing the State Natural Reserve in 1982. Tufa is a chemical deposit of calcium carbonate, which is the same compound that makes limestone. Tufa is still being deposited at Mono Lake. The basic process of its formation is known through research at Mono Lake and

**Why it's important:** Mono Lake Tufa State Natural Reserve is one of the rare places in the world that contain such a unique group of geologic features. The tufa formations are notable for their unusual shapes and abundance. Extensively studied by scientists, they have aided our understanding of the climate history of this region. The extremely high salinity and alkalinity of Mono Lake has created a rare ecosystem, supporting a complex food chain of green algae, brine shrimp and alkali flies, and more than 80 species of migratory birds.

elsewhere around the world, but scientists still do not fully understand the details of how tufa forms. For example, although organisms such as algae are found with tufa, their roles in the process of its formation are still uncertain.

Tufa towers rise vertically from the lake and shoreline as chimney-like formations up to 30 feet high; some are estimated to be several hundred years old. The towers were progressively built upwards beneath Mono Lake when freshwater springs carrying dissolved calcium discharged from the lake bottom and chemically reacted with the bicarbonate-bearing lake water to deposit calcium carbonate. Standing individually or in clusters, some towers still have spring water flowing out of their summits, sides, or bases. Because the artificial diversion of the inflows of fresh water caused the lake's level to drop, we are able to see the towers exposed today. As the lake rises eventually to its legally mandated level of 6,392 feet above sea level (it was at 6,383 feet in 2008), some of the presently exposed towers will again be submerged.

On the dry land adjacent to the lake are many sand-tufa structures, which are composed of pumice sand cemented by calcium carbonate. They are masses of tubes and columns suggestive of tree roots or worm burrows, although they did not form by biologic processes. Instead they formed by the movement of calcium-bearing freshwater springs and groundwater through layers of loose pumice sand near the shore of Mono Lake. These layers were saturated with the highly saline lake water that also helped form the tufa towers. As the fresh water encountered the more dense lake water in the sand, the fresh water rose upward. Where it was in contact with the saline water, deposits of calcium carbonate formed to cement the sand grains together. As the lake water receded—starting in 1941—the layers of pumice sand were exposed to erosion by wind. Because the cemented pumice sands were resistant, the loose sands were eroded away and the harder sand-tufa structures remained behind. Some of the structures have flat layers of caliche (a type of calcium carbonate) at their tops, which likely formed at or just below the ground surface shortly after the lake receded. This caliche layer protects the underlying fanciful and delicate tufa sand structures from erosion.

## Final Thoughts

Many of the lakes in the Basin and Range are but small remnants of larger predecessors that formed while glaciers covered the northern and southern latitudes of the continents.

*Written by Chris Higgins, California Geological Survey, 2010*
*Photos: Mike Fuller*

GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 38

# Red Rock Canyon State Park

Photo: Will Harris

## Geomorphic Provinces and Boundaries

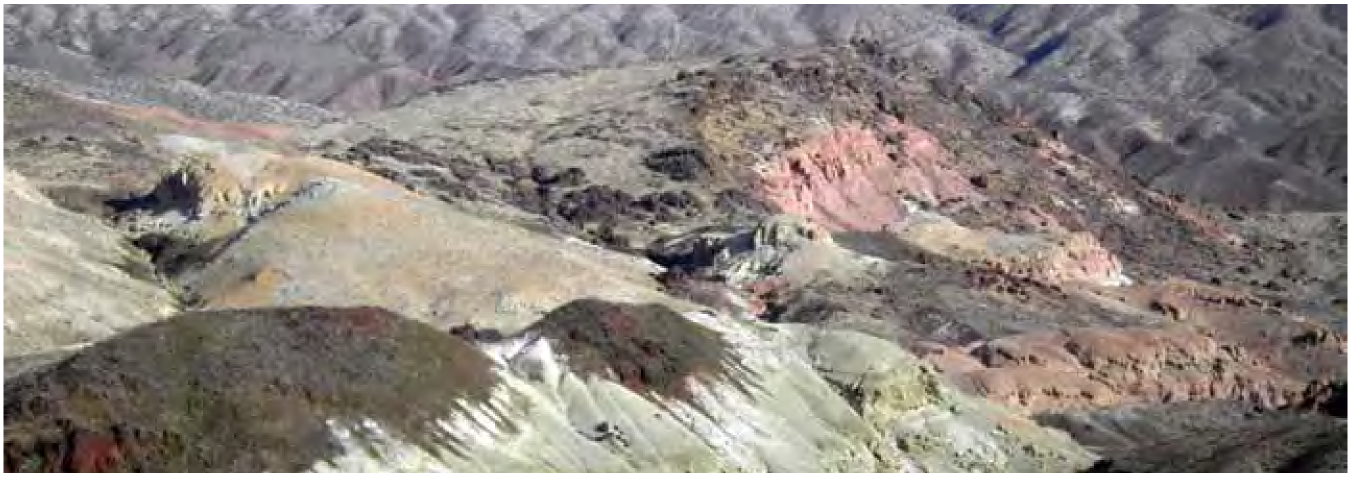
Red Rock Canyon lies in the Basin and Range geomorphic province which features large north-south trending mountains and valleys. This park is just east of the southern Sierra Nevada and north of the Mojave Desert geomorphic province. Features and rocks from the neighboring geomorphic provinces can be found around the park. The east–west trending Garlock Fault, just south of the park, separates the Mojave Desert from the Basin and Range. The El Paso Fault, a branch of the Garlock Fault, traces northeast through the park, near the crest of the El Paso Mountains. During two periods (55 to 65 and 5 to 20 million years ago) this area subsided and over 5,000 feet of sediments and volcanic materials accumulated. Later movement along the El Paso Fault uplifted the sediments, exposing them to erosion that formed the badland topography.

### Process/Feature:

Basin sedimentology along province boundaries, Paleocene and Miocene fossils, and scenic cliffs

## Faults

The Garlock Fault is an active left-lateral fault (one side of the fault moves to the left relative to the other side). The Garlock Fault runs northeasterly from its intersection with the San Andreas Fault in the Tehachapi Mountains to the Avawatz Mountains south of Death Valley. The amount of displacement on the Garlock Fault is estimated at 40 miles.



**Why it's important:** Red Rock Canyon's rugged beauty has been the scene in western and science fiction films such as Stagecoach with John Wayne (1939), The Mummy with Boris Karloff (1933), 20,000 Leagues Under the Sea (1954), and Jurassic Park (1993).

The colorful badlands, cliffs and canyons provide more than pretty scenery and a backdrop for movies. Hidden behind the scenes in the layers of rock is what amounts to paleontologists as a treasure trove. For almost a century, paleontologists have been combing through these layers and making important discoveries about the history of mammalian life in these parts.

The El Paso Fault formed in response to the tearing caused by the Garlock Fault. Strain just north of the Garlock's trace pushed a block of terrain upward, causing the landscape to break along the northeasterly oriented El Paso Fault thus uplifting the El Paso Mountains—a typical "fault block." Most of the uplifted rock has since been eroded away. The tilted layers of rock revealed on the fault's up-thrown block, north of the trace of the El Paso Fault, are displayed with younger layers atop older layers in the colorful sidewalls of the southeast-draining canyons of Red Rock Canyon.

## Rock Formations

The strata are divided into two major groups: the Goler Formation (55 to 65 million years old) and the overlying Ricardo Group (5 to 20 million years old). A portion of the Ricardo Group is the famously fossiliferous Dove Springs Formation.

The Goler Formation is more than 3,000 feet thick. It is best viewed in Last Chance Canyon. Long before the El Paso Mountains existed, about 65 million years ago, the detritus from the weathering uplands (long vanished) began to accumulate and the first coarse of sediments of the Goler Formation were deposited on eroded outcrops of basement rock. Boulders and cobbles tumbled onto the eroded surface first, followed by coarser sands and cobbles indicative of alluvial fans deposits near a mountain flank. Since the 1990s, researchers have systematically unveiled a wealth of vertebrate fossils (unrivaled west of the Rockies) in these 55 to 65 million year-old layers.

### What you can see:

Colorful cliffs and canyons made up of layers of sediments and volcanic deposits. Classic desert landforms such as alluvial fans, slot canyons, dry waterfalls, and erosion pedestals are beautifully displayed.

The present topography began to form about 18 million years ago as movement initiated on the Garlock Fault and its related splays like the El Paso Fault. Major drainages for the area, such as Red Rock Canyon and Last Chance Canyon, were established shortly before this time, though they looked much different then. As the El Paso Mountains were uplifted, the drainages were able to maintain their courses across the fault block by eroding the uplifted rock as it rose incrementally over millions of years.

The uplift along the El Paso Fault further tilted the Goler Formation to the northwest. Concurrently, the initial sediments of the Ricardo Group were deposited in a basin atop the eroded Goler Formation.

The Ricardo Group contains the red sandstone beds for which this region is famous. It consists of nearly 7,000 feet of coarse volcanic ash, lava flows, sandstones, lake-deposited silts and clays, and sandy gravels. Most of these deposits contain or consist entirely of volcanic ash, and some are inter-layered with lava flows. This is fortuitous as geologists can determine the ages of these deposits with good precision, providing an unusually well-defined timeline for the Ricardo Group.

Deposition of the Ricardo Group spanned 8 to 18 million years, ending about five million years ago. The pink and white ash beds and lava rock record the evolution of the Basin and Ranges geomorphic province, when many volcanic vents and fissures were erupting within and near the expanding (rifting) province.

Although the Ricardo Group is the thickest geologic deposit found in the Red Rock area, it was originally much thicker. The upper portion of the formation was eroded due to renewed uplift on the El Paso Fault. The fault movement also caused the formation to be tilted back to the northwest, allowing the southeast-draining desert washes to cut down through the soft strata of the Ricardo Group, dramatically exposing the colorful sediments on the canyon sidewalls. The formation's dramatic flare has been

increased by water from periodic rainfall that flows down over the exposed layers, eroding away the softer beds leaving the effect of fluted columns.

Much of the red and pink hues of the Ricardo Group derived from oxidization of iron-bearing minerals. The white layers consist dominantly of volcanic ash.

Within the upper part of the Ricardo Group lies the famous Dove Springs Formation which contains over 100 types of fossils of extinct plants and animals, including woody plants, giraffe-like camels, elephants, three-toed horses, rhinoceros, saber-toothed cats, primitive dogs, skunks, and rodents. Deposited between 7.5 and 12.5 million years ago, the Dove Springs formation offers a unique four million-year-long record of life in a well-defined timeline.

## Final Thoughts

The fossil treasure troves of the Goler and Dove Springs Formations are being compared with fossils found elsewhere in North America and even Asia, to help understand the evolution of mammals (including early primates) and their migration across continents. For example, Anza-Borrego Desert State Park contains an amazing assemblage of more recent mammal fossils dating back less than five million years.

*Written by Will Harris, California Geological Survey, 2010*
*Photos: Mike Fuller (except where noted)*

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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 39

# Transverse Ranges Geomorphic Province

The **Transverse Ranges** are a complex series of east-west trending mountain ranges and valleys that strongly contrast with the northwest trend of the adjacent Coast Ranges and Peninsular Ranges. The section of Cenozoic sedimentary rocks within this province is one of the thickest in the world and regional structural trends are significant in the formation of important oil field structures.

The western limit of the province contains the islands of San Miguel, Santa Rosa, and Santa Cruz. The eastern limit extends into the Mojave Desert, and includes the San Bernardino Mountains to the east of the San Andreas Fault. Within the Transverse Ranges, the San Bernardino and San Gabriel Mountains contain some of the highest peaks in southern California, ranging from 10,000 to over 11,500 feet above sea level.

## Tectonic Setting

The Transverse Ranges are caught in a geological vise that has been squeezing them for the past 20 million years, from south to north producing high amplitude compressed folds and faults. The troughs of the folds became deep marine basins and the peaks are expressed as the ranges. The exceptionally thick sediments were at first rapidly deposited into the deep marine basins, then with continued compression were pressed up into the ranges. Tectonic models suggest that the Ranges rotated nearly 100 degrees clockwise due to plate tectonic movements.

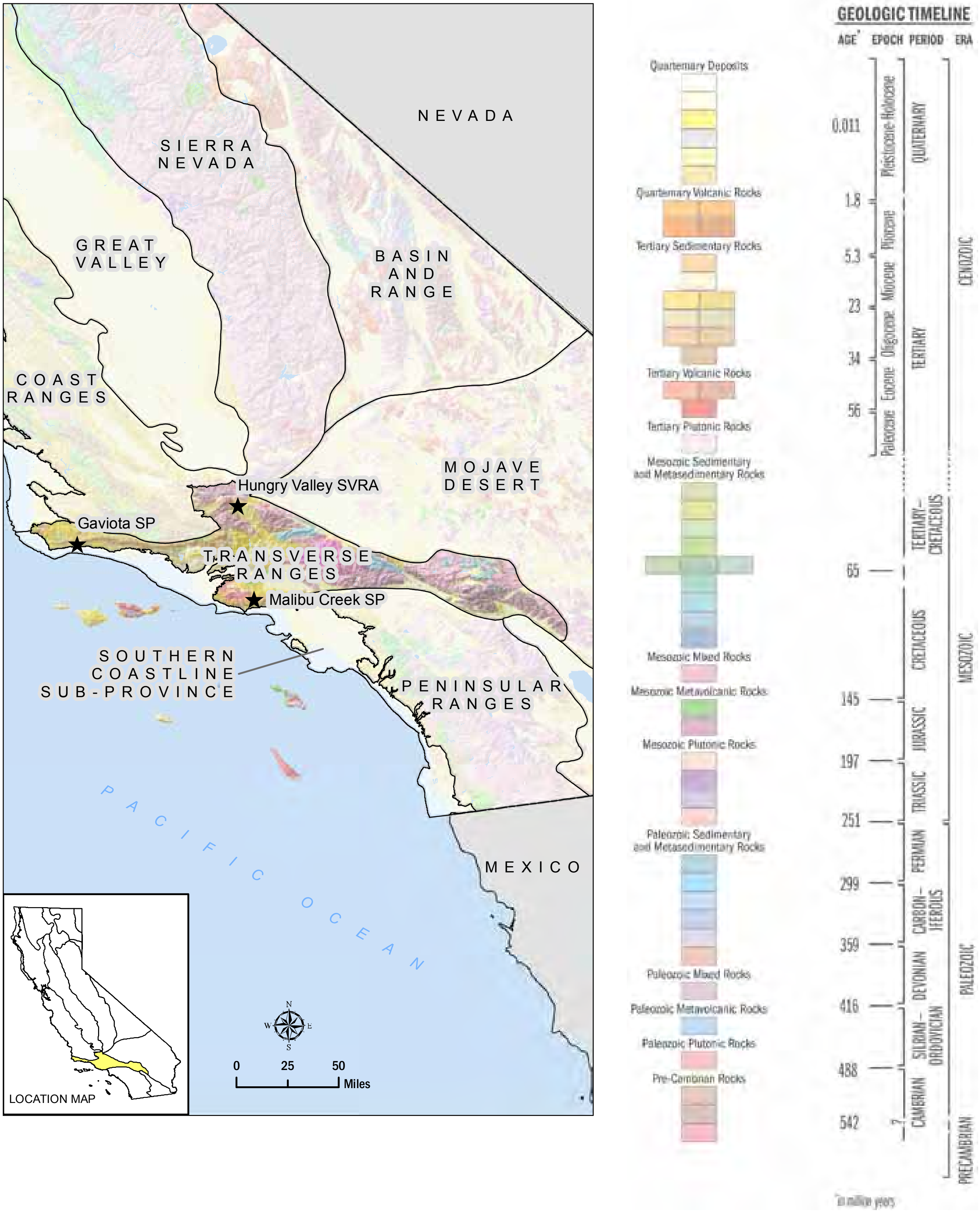
The Transverse Ranges are bisected by the San Andreas Fault system representing a complex section of the tectonic plate boundary. This compression is thought to result from what is called the “Big Bend” in the San Andreas Fault. Overall, the trend of the San Andreas is north by northwest but in this section it bends counterclockwise, that is more northwest. In simple terms, the lands northeast of the boundary are riding on the North American plate with its northwest heading. The lands southwest of the boundary are riding on the more northerly drifting Pacific plate which is pushing into the North American plate.

## GeoGems

**Hungry Valley State Vehicular Recreation Area, Gaviota State Park,** and **Malibu Creek State Park** are the GeoGems that represent the Transverse Ranges. Between five and 20 million years ago, the sedimentary rocks at Gaviota and Hungry Valley and the volcanic rocks at Malibu Creek were deposited in oceanic basins that have been so compressed into folds and faults that they became part of the mountains. Hungry Valley lies along the San Andreas Fault at a point where the Coast Ranges, the Transverse Ranges, and the Sierra Nevada all merge near the boundary of the Mojave Desert geomorphic province.

*Written by Mike Fuller and others, California Geological Survey*
*Photo: Pam Irvine*

## Simplified Geologic Map | Transverse Ranges Geomorphic Province



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Geological Gems of California State Parks, Special Report 230 – Fuller, M., Brown, S., Wills, C. and Short, W., editors, 2015 Geological Gems of California, California Geological Survey under Interagency Agreement C01718011 with California State Parks.

GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 40

# Hungry Valley SVRA

State Vehicular Recreation Area

## Diverse Expression of the San Andreas Fault

In general terms, the San Andreas Fault is a system of faults that has evolved through time. The San Andreas Fault system marks the boundary between the Pacific and the North American tectonic plates which are sliding past each other.

In places, the San Andreas Fault is a well-defined single strand. In other places, it consists of several roughly parallel faults (referred to as strands). Sometimes the fault interacts with other faults in complex ways with active movement shifting to another trace and initiating a new active strand.

### Feature/Process:

Seismic and tectonic geology along the plate boundary, and fossils

Along the lengthy plate boundary the net movement is right-lateral (one side of the fault moves to the right relative to the other side). With slight jogs or turns along the fault, secondary zones of compression form hills and zones of extension form basins.

As the plate boundary develops and movement shifts from one strand to another, the focal points of secondary compression and extension may shift. The Ridge Basin is a case where an extensional ("pull apart") basin came to be squeezed up in a zone of compression as movement shifted from one fault strand (the San Gabriel Fault) to a newer one (the current San Andreas Fault). This is called "basin inversion" by geologists who delight in the fact that uplifted sediments that were once deeply buried are now exposed and available for study. The broader setting of this adjustment zone is called the Big Bend of the San Andreas Fault.

**What you can see:** Tilted and folded sedimentary rocks, differential erosion, “bad lands” topography, fossil burrows of predatory insects (tiger beetle larvae), and fossil clams and snails.

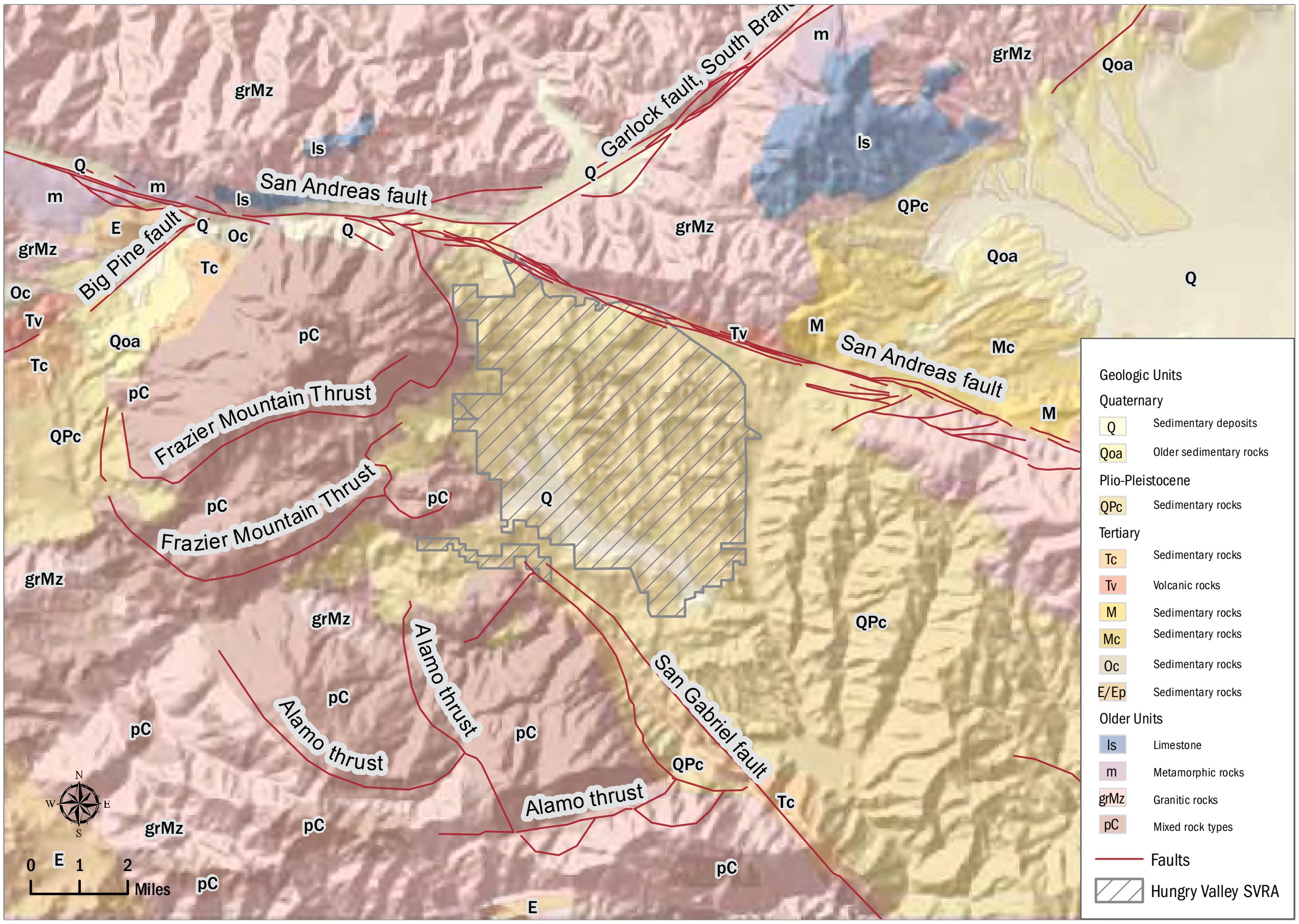
**Why it’s important:** Hungry Valley SVRA lies in the heart of a complex geologic structure know as the Ridge Basin. The highly deformed rocks within the park bear stark witness to the tremendous forces that characterize the interplay between the San Andreas and San Gabriel Faults, which bound the basin and the park.

## Ridge Basin Formation

The Ridge Basin began to form approximately 11 million years ago. Movements on the San Gabriel and San Andreas Faults pulled the earth’s surface apart creating a basin. At that time, the San Gabriel Fault was the region’s principal tectonic feature, not the San Andreas. Like the San Andreas, it accommodated principally right-lateral movement with secondary vertical movement.

The basin continued to subside and simultaneously to collect sediment eroded from the flanking range that was uplifted along the San Gabriel Fault. More than 30,000 vertical feet of sediment accumulated in the basin. The sediment deposits provide a seven million year long record of the interplay between basin development and fault movements.

During this period, the primary motion changed from vertical to horizontal (strike-slip faulting) and more of the movement was being taken up on the San Andreas Fault. About four million years ago, tectonic forces were transferred to the San Andreas Fault and the San Gabriel Fault became much less active.



Stress from the San Andreas Fault compressed and uplifted the sedimentary rocks that had filled the Ridge Basin. These uplifted basin rocks have been dissected and eroded with many rugged canyons.

Resistant sandstone and conglomerate layers interlace with weaker shale and siltstone layers. This contrast in resistance to erosion creates the badlands topography that characterizes the eastern half of the park.

**Movements on the San Gabriel and San Andreas Faults pulled the earth's surface apart creating a basin.**

The compressive forces exerted by the San Andreas Fault as it bends westward at Frazier Mountain led to the creation of the Frazier Mountain and Dry Creek Faults. Movement along these compressive faults resulted in older, metamorphic basement rocks being placed on top of (thrust over) the younger sedimentary rocks of Hungry Valley.

## Changing Environment

The texture and composition of the sediments and the presence of key fossils indicate that the evolving basin hosted a sequence of several different environments including a deep lake, a shallow lake, a marine embayment, and alluvial fans. Close examination of finer-grained sandstones and mudstones will often reveal tubular shapes randomly distributed through the rock. These are the fossil burrows of predatory insects (tiger beetle larvae) that were hunting on the mud flats on the shores of ancient streams and quiet backwaters.

Other fossils that may be observed include clams and snails. One may also discover beds that contain layers of densely packed fossil shell fragments (fossil “hash”). These are what paleontologists refer to as “death assemblages”, i.e. the animals die and their remains are washed into quiet backwaters or eddies, where they are fossilized.

## Final Thoughts

The Ridge Basin is a virtual laboratory where the “evolution” of a plate boundary can be studied in detail. Lessons learned here can be applied to other areas that seem to be currently evolving in similar ways, such as the Salton Sea region.

*Written by Stephen Reynolds, California Geological Survey*
*Photos: Stephen Reynolds*

Geological Gems of California State Parks, Special Report 230 – Fuller, M., Brown, S., Wills, C. and Short, W., editors, 2015 Geological Gems of California, California Geological Survey under Interagency Agreement C01718011 with California State Parks.

# Gaviota State Park

## Miocene Monterey Formation

The Monterey Formation visible at Gaviota State Park is a major source of petroleum in southern California. Prior to the arrival of the Europeans, the Chumash people used tar that seeped from these rocks to waterproof their ocean-going canoes. The tar seeps barely suggested the vast underground reservoirs of petroleum that were eventually discovered.

### Features:

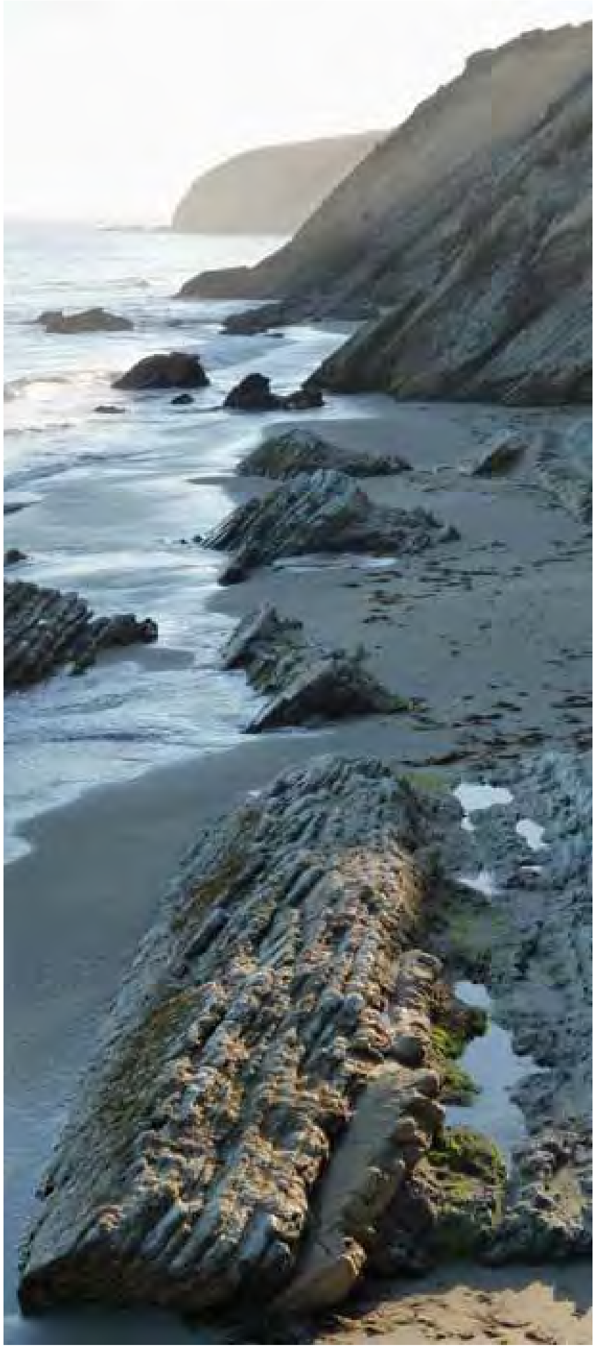
Sedimentology of an uplifted Miocene ocean basin, and fossils

Strikingly different from the rich source rocks are the thick layers of diatomaceous sediment (deposits of diatoms—the “skeletal” remains of microscopic plankton). Abundant microscopic pores make the material very lightweight and ideal for filtering impurities out of various solutions. Once used for refining sugar and beer, diatomite is better known for its uses in swimming pool filters and as filler to reduce the weight of concrete. There are over 300 other industrial uses.

**Why it's important:** The coastal bluffs at Gaviota State Park reveal a 500-foot thick cross-section of the geographically extensive Monterey Formation. Offshore and inland, petroleum geologists have extensively explored underground for oil reservoirs within this rock sequence and probed its depths to understand the genesis of this important oil source.

The naturally cemented, bluff faces resist wave erosion and are tilted to display multiple layers like the pages of a book. The geologic layers contain some nicely preserved fossils—even the complete skeleton of a halibut-like fish.

During the Miocene (5 to 23 million years ago), the precursor sediments of the Monterey Formation were deposited in deep quiet waters far offshore from the present onshore location. Enormous quantities of diatomaceous skeletons rained down through the oceanic water column to settle on the ocean floor. Layer upon layer buried the previous extensive deposits. The diatomaceous ooze of planktonic debris was compressed over time into shale layers that are cumulatively as thick as 3,000 to 6,000 feet. These rocks now extend from Point Arena (Mendocino County), north of San Francisco Bay, to Dana Point in southern Orange County.



Thin layers are visible in the diatomaceous shale, which give it a platy appearance. The texture indicates deposition in quiet water far from sources of other (such as land-derived) sediment. About 20 million years ago, dynamics between the movements of the tectonic plates stretched the crust which consequently subsided, oceanic basins formed along the continental margin. These basins filled with sediment until around six million years ago. Subsequently, the deposits were compressed against the continent and uplifted along with the surrounding region.

Volcanoes to the east were erupting as the Monterey Formation was forming; large quantities of ash were deposited on the ocean surface and trickled down to the ocean floor. This is reflected in the submarine ash beds (tuff) at the base of the Monterey Formation. Because of its thickness and persistence in the region, this tuff unit is known to geologists as the Obispo tuff member of the Monterey Formation.

## Fossils

The Monterey Formation contains fossils in the vicinity of the park. Fish scales are common along bedding planes, and some complete fish skeletons (halibut-type fish) have been found. Whale bones and plant fossils have also been discovered among the layers of the rocks. The microscopic diatoms make up the bulk of the Monterey. Of course, being microscopic, the beauty and variety of the fossilized plankton are best appreciated under a microscope where thousands of elegant shapes can be seen.

**What you can see:** Fossil-rich, tilted shale and diatomite beds formed on the ocean floor millions of years ago.

## Dip Slope Bedding

The multiple layers of the Monterey shale are beds of material deposited on the ocean floor in a nearly horizontal position, and subsequently deeply buried and compressed. Since the time of deposition, the layers have been folded and the once-horizontal beds are now tilted. West of the pier, the tilted beds are at the same angle as the slope face, so the cliff face angle is the same inclination as the tilted beds. Along cross-fractures, the layers break, giving the appearance of pages of a book—frozen in stone.

By measuring the geometry of layers in the subsurface and determining how and when the rocks were deformed in their journey from deep ocean basin to the Santa Ynez Mountains, we are led to a deeper understanding and appreciation for the powerful and relentless tectonic forces involved.

## Interesting Unique Layers

The conglomerates (cemented layers of cobbles within the formation) exposed in the bluffs include many interesting features. Some of the conglomerates are impregnated with natural tar. Some of the conglomerates contain pebbles made of phosphate minerals.

Layers of volcanic ash are found here and there. An 18-inch-thick layer of volcanic ash lies 500 yards west of Canada del Cementario. To the east for three miles, the layers are intensely folded due to deformation that occurred while the sediments were still soft and plastic. The soft sediment deformation may have developed from the slumping off the edge of the continental shelf and down the continental slope to the deep ocean floor.

## Final Thoughts

Being economically important, the Monterey Formation has elicited a great deal of study over the last hundred or so years. Despite extensive research, many questions of its origin remain.

*Written by Jeremy Lancaster, California Geological Survey*
*Photos: Jennifer Lotery*

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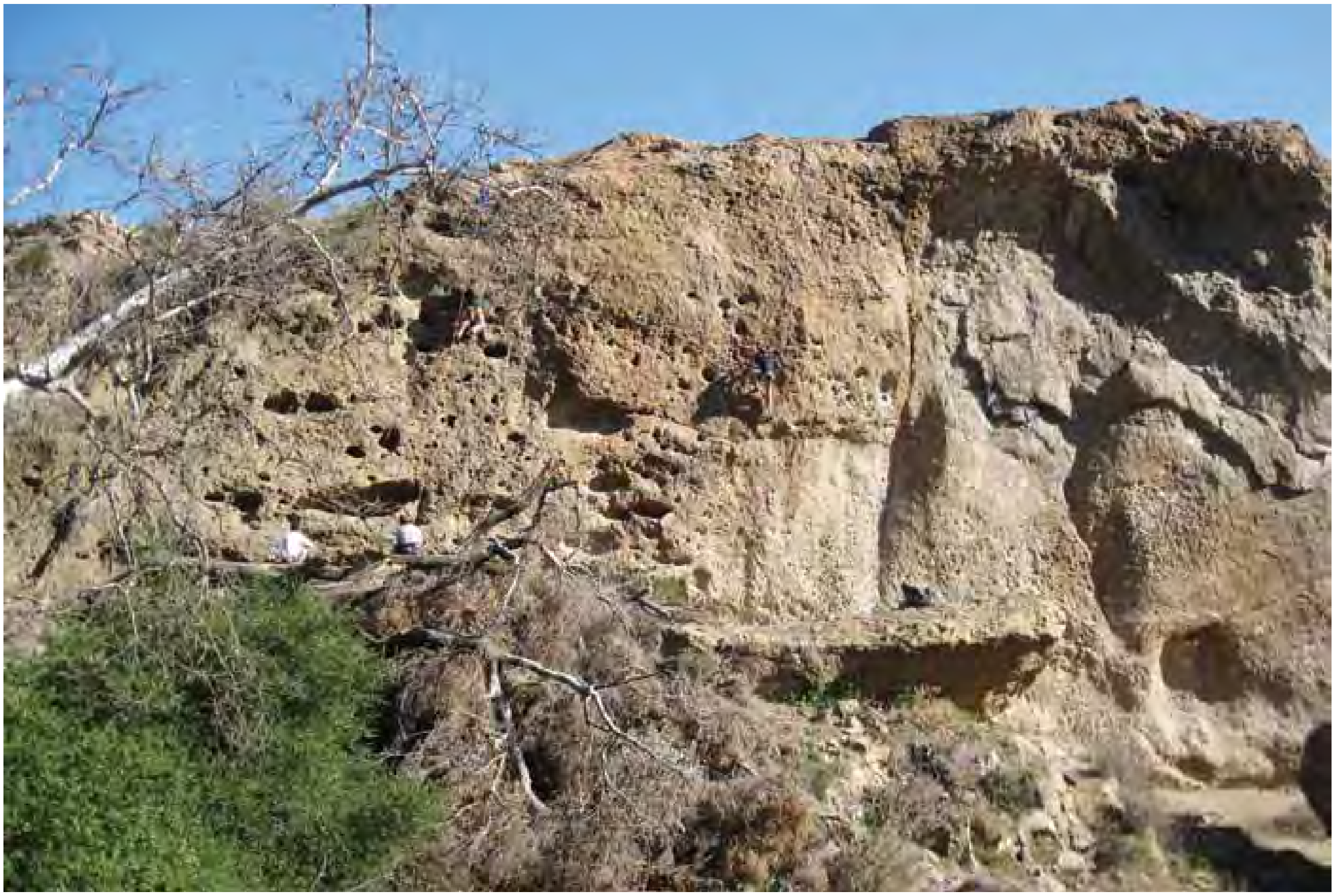
# Malibu Creek State Park

## Conejo Volcanics

**Features/Process:**
Volcanology of an uplifted Miocene ocean basin, and pillow basalts

Crossing the central section of Malibu Creek State Park are tilted layers of the Conejo volcanic rocks that form prominent east to west aligned ridges. These include Brent's Mountain and Goats Butte. The exposures of the Conejo volcanic rocks contain abundant clues that reveal the geologic history of the area. During the Miocene Epoch, the Conejo Volcanics were extruded onto the sea floor from approximately 17.4 to 15.9 million years before present. The types of volcanic rocks that comprise the Conejo Volcanics are lava (basaltic and andesitic) flows, pillow basalts, tuff, and volcanic breccias. These rocks are exposed in the road cuts, cliffs, ridges, and valleys—they are generally dark brown to dark reddish brown in color. Some of these rocks contain abundant vesicles which were air bubbles or pockets trapped in the lava as it cooled.



**Why it's important:** Malibu Creek State Park contains excellent exposures of the Conejo Volcanics that cover large portions of the modern Santa Monica Mountains of the Transverse Ranges geomorphic province. The Conejo Volcanics are one of several Miocene volcanic fields along the California coast that erupted in response to a major reorientation of the tectonic plate boundary between the North American tectonic plate, the subducting Monterey microplate, and the better-known Farallon plate. The reorientation caused local areas of extension and crustal thinning. The molten rocks below the thin oceanic crust ascended through the crust along fractures to the surface and erupted as volcanic rocks.

Limestone with oyster shells and other marine fossils formed within the submarine volcanic field. Submarine eruptions of basaltic lava typically produce pillow-shaped structures called pillow basalts. Although the pillows were later broken into multitudes of pieces (breccia); vestiges of these underwater forms remain recognizable. Later in the eruptive life of the volcanic field, the region was elevated above sea level as evidenced by pieces of petrified wood in the later lava deposits.

## Why They Formed?

The Conejo Volcanics formed when the eastern Pacific oceanic tectonic plate and the Monterey microplate were subducted beneath the North American tectonic plate, causing upward and lateral land surface swelling (dilation) and then extension (deflation). Many basins formed along the continental margin due to extensional faulting, and these basins then filled with sediment. That accumulated sediment is now visible as sandstone, siltstone and pebbly sandstone. Volcanic vents occurred along the bottom and on the margins of the basins as magma rose along faults and zones of weakness in the crust. As the basins continued to fill with sediment, they were also filled with layers of volcanic rock in the form of basalt flows, pillow basalts, submarine ash (tuff), and volcanic mudflows. The rocks formed from these diverse processes are now considered part of the Topanga Group.

*Photo: Jeremy Lancaster*

**What you can see:** Volcanic pillow basalts which formed on the ocean floor.

## Pillow Basalts and Breccias

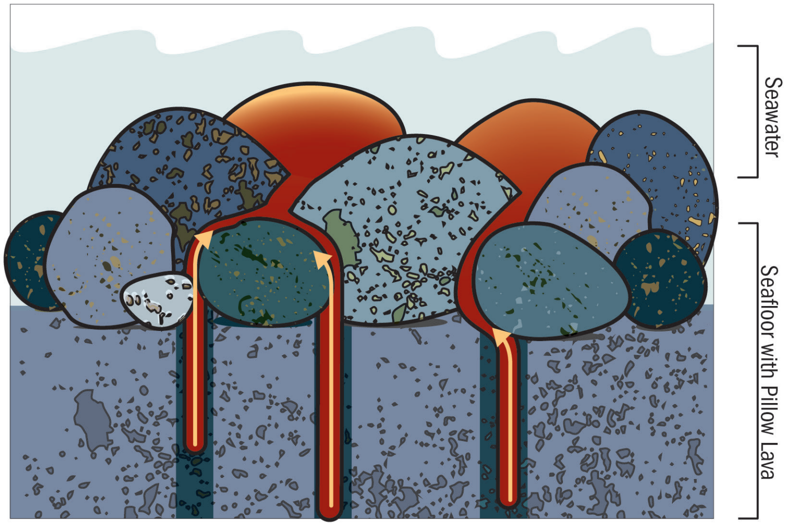


*Illustration: A. Carney*

As basaltic lava oozes from fissures and contacts cold seawater, a crust forms around the blob of extruded lava. As pressure builds, the crust breaks and more fresh lava extrudes like toothpaste squeezed from a tube. Each extrusion of lava has an irregular lower surface and a smooth, convex upper surface, superficially resembling a pillow. Further eruptions cause hot lava to break out and form more “pillows.” This pillow texture is common in underwater basaltic flows and is diagnostic of an underwater eruption environment. If underwater eruptions are continuously repeated, a thick sequence of pillows may be formed.

Between episodes of lava eruptions of pillow basalts other biological activity occurred on the sea floor. Marine organisms likely thrived upon and congregated around these pillow basalts and associated hot spots. The Conejo Volcanics contain beds of volcanic sandstone with fossils.

## What is a Pillow Basalt Breccia?

Sometimes pillow basalts will be erupted into a relatively quiet environment and the pillow structures are preserved intact. In other areas, the pillows may be broken or otherwise deformed by later earth movements. Most of the pillow basalts in Malibu Creek State Park are pillow basalt breccias. A breccia is a type of rock that contains very angular, broken fragments in a matrix of finer grained material. Pillow basalt breccias tell us that something catastrophic occurred on the sea floor, such as a submarine landslide.

Periods of quiet do not last forever on the sea floor where volcanic activity is intermittently active. Because of the extension along the continental margin during Miocene time, portions of the sea floor would commonly drop downward to form basins. As a result, steep slopes formed along the margins of these basins and became areas where sediment from the continent was deposited underwater. Submarine landslides were commonplace along these steep underwater slopes and deposited material in the basin bottoms. Eventually, thick sequences of pillow basalts, volcanic sands, and other sediment were caught up in these landslides. The outcome is simple to picture: a thick sequence of pillows are broken up, deformed and then re-deposited on the ocean floor as slide debris. The uniform stack of pillows then becomes a breccia, with only very little original pillow structure remaining.

## Final Thoughts

This land is being squeezed in a tectonic vise with the continental plate on one side and the oceanic plate on the other. The effects are apparent on so many scales, ranging from fragmented rocks to tilted beds of marine deposits being thrust forward and upward during powerful earthquakes.

*Written by Jeremy Lancaster, California Geological Survey*
*Photos: Pam Irvine (except where noted)*

# Mojave Desert Geomorphic Province

Photo: California State Parks

The Mojave Desert is a broad interior region of isolated mountain ranges separated by expanses of desert plains. Sometimes referred to as the high desert, elevations in the Mojave Desert generally range between 3,000 to 6,000 feet. Because of the enclosed interior drainage, rainwater either seeps into the ground or is evaporated, resulting in many playas. Within the province, there are two important fault trends that control topography: a prominent northwest trend and a secondary east-west trend (an apparent alignment with the Transverse Ranges).

## Tectonic Setting

The rocks in the Mojave Desert are progressively older from the west toward the east. Some of the oldest rocks (about 1.7 billion years old) in California are exposed in the eastern Mojave Desert. Here also are remnants of what was the western continental shelf during the formation of the Appalachian Mountains and the Pangaea supercontinent.

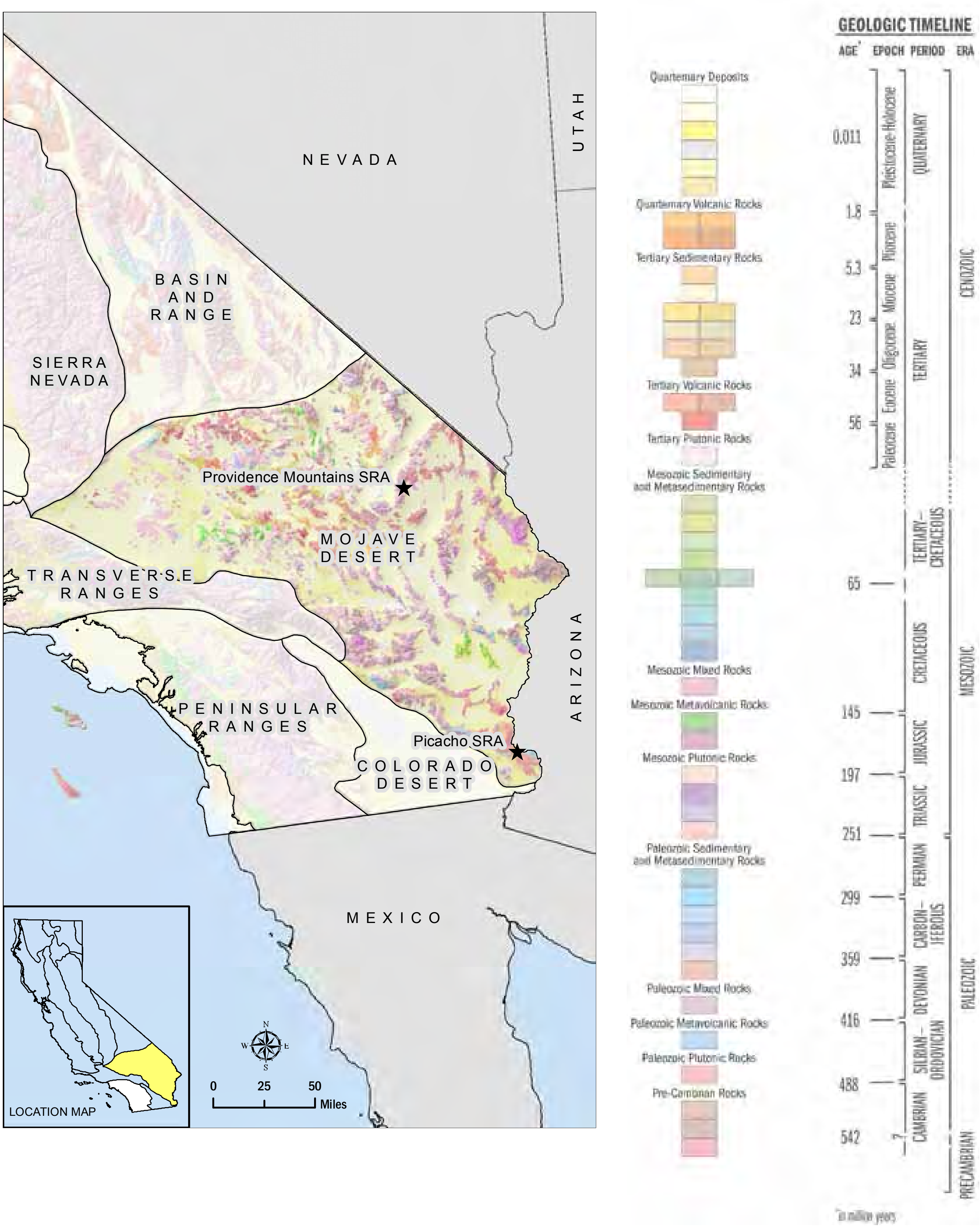
The Mojave Desert geomorphic province's wedge-shaped appearance is due to the Garlock Fault along its northern boundary (the southern boundary of the Sierra Nevada) and the San Andreas Fault along the southern boundary. Like the Basin and Range geomorphic province, this region has been growing from east to west. It is also being sliced north to south along a set of faults (the eastern California shear zone) that operate similar to and parallel with the San Andreas Fault.

## GeoGem

**Providence Mountains State Recreation Area** and **Picacho State Recreation Area** are the GeoGems representing the vast and complex Mojave Desert that spans so much geologic time. Within Providence Mountains State Recreation Area, Mitchell Caverns is a National Natural Landmark and in a way epitomizes the geomorphic province's very long connection to global geologic events. In this very arid desert, the limestone (deposited as much as 299 million years ago on the continental shelf, then accreted onto the continent) has intermittently dissolved during periods of high groundwater that coincide with glacial periods as recently as 11,500 years ago. The dissolved minerals then precipitated as cave formations with chemical signatures of the changing climate. These recordings of the Ice Ages are preserved in the cave formations in Mitchell Caverns.

*Written by Mike Fuller and others, California Geological Survey*
*Photos: Mike Fuller*

# Simplified Geologic Map | Mojave Desert Geomorphic Province



## NOTES:

Prepared by California Geological Survey, Department of Conservation | www.conservation.ca.gov/cgs
for California State Parks | www.parks.ca.gov

Geological Gems of California State Parks, Special Report 230 – Fuller, M., Brown, S., Wills, C. and Short, W., editors, 2015 Geological Gems of California, California Geological Survey under Interagency Agreement C01718011 with California State Parks.

# Providence Mountains SRA

National Natural Landmark 1975 | State Recreation Area

## Oldest Rocks in the State Park System?

The Providence Mountains State Recreation Area lies within the Mojave Desert geomorphic province of southern California, characterized by a series of isolated mountain ranges with intervening valleys and desert plains. In the eastern portion of this province, the rocks are much older than in the west. In the recreation area, the oldest rocks are called gneiss, a highly metamorphozed rock, and they are the oldest rocks in the California State Park system. They are Precambrian in age and have been dated at approximately 1.7 billion years old, nearly one-third the age of the earth itself!

### Features:

Geologic beginnings of California, caverns, and speleothems

### What you can see:

- Limestone and gneissic metamorphic rocks
- Limestone caves and dripstone formations (speleothems), a record of the region's past climate

**Why it's important:** The Providence Mountains State Recreation Area contains the oldest rocks in the state park system and some of the most spectacular limestone caves in all of California. The caves are important to visitors for their spectacular beauty, but they also provide abundant information about the geologic and climatic history of the region.

## What Gneiss Represents

Gneiss is a rock that has been subjected to immense heat and pressure in the earth's crust. During metamorphism, minerals partially melt and re-crystallize, orienting themselves in response to pressure. It is the orienting of light and dark minerals that appears as banding or layering. The depth in the earth's crust required to cause rocks to metamorphose into gneiss is on average about 15 miles deep, with a temperature of roughly 1,000° Fahrenheit.

The gneissic rocks of the State Recreation Area represent the metamorphism of sedimentary and igneous rocks during a mountain-building event that occurred on the ancient western continental margin of what is now North America. Because of the depth required to metamorphose the pre-existing rocks, we know that 15 miles of overlying sediment and rocks have been uplifted and removed by erosion to bring these rocks to the surface.

## How Long Did This Take?

In the area that is now the Providence Mountains, the gneiss was exposed at the earth's surface and sediments were deposited on top of it during the Paleozoic Era (570 to 245 million years before present). A contact between the gneiss and the overlying Paleozoic sedimentary rocks represents an enormous gap of time in the geologic record, an unconformity. This particular unconformity is termed the "great unconformity." It represents 1.2 billion years of erosion (all the material overlying the gneiss was eroded away) and it extends across much of the western United States.

In the vicinity of Mitchell Caverns, the contact between the gneiss and Late Paleozoic Bird Spring Formation is not an unconformity, but is a fault contact created by the East Providence Fault.

## Limestone and Limestone Caves

The limestone caverns occur in the Late Paleozoic (~299 to 251 million years ago) Bird Spring Formation. The Bird Spring, composed chiefly of limestone, represents a period of stability along the western edge of the continent where a warm and shallow sea contained abundant calcium carbonate shelled organisms that fell to the bottom of the ocean, eventually forming limestone.

Many tectonic events have affected the area since the deposition of the Bird Spring, such as the break-up of the supercontinent Pangaea, mountain building during the Mesozoic and Early Tertiary, and extensional faulting and volcanism during the Tertiary. Today, we see the oceanic deposits of the Bird Spring capped by Miocene volcanic rocks, hundreds of miles away from, and elevated above our modern Pacific Ocean.

## Cave Formation

Being composed of calcium carbonate, the Bird Spring limestone is slightly soluble in water. Dissolution is accelerated by the addition of carbonic acid from rainwater and decaying vegetation found in the soils overlying the caves. Taking place in the arid desert, this process is very slow.

During the Ice Ages (~1.6 million to ~11.7 thousand years before present), this region was likely much colder and wetter. The beginning of the formation of the solution caves at Mitchell Caverns was even earlier and is thought to be as much as 12 million years ago, during prevailing warm and wet tropical climate conditions. The increased precipitation would have percolated into the mountains along fractures and gradually dissolved the limestone, forming cavities and dripstone. After thousands of years, the openings became large enough to allow for increased flow of groundwater and accelerated cave growth. It took many thousands to a million years for that accelerated flow to form 3-foot-wide solution cave passages.

## Dripstone—Beauty and Scientific Value

Without question the dripstone formations or speleothems are beautiful and pleasing to the eye, but for scientists who study past climates, they are also a gold mine of information. Each layer contains chemical clues to the climate during which it formed. Analyses of speleothem growth rates and chemical composition can show past patterns of climate change.

Elsewhere, in more recently active speleothem deposits, laminations that form along the growth axes of stalagmites have been measured, isotopically analyzed, and dated. From the analyses, scientists have been able to differentiate wet from dry periods and cold from warm periods. From these studies, past climate change events have been traced back as far as 250,000 years. The resulting data from the studies have also been calibrated by comparison with historically recorded periods of cold, such as the “little Ice Age,” and the “medieval warm period.”

## Final Thoughts

Eventually, the analysis of speleothem deposits in Mitchell Caverns and the surrounding region may contribute to modern climate change models and help us to respond and adapt to future climate change.

*Written by Jeremy Lancaster, California Geological Survey*
*Photos: California State Parks*

Geological Gems of California State Parks, Special Report 230 – Fuller, M., Brown, S., Wills, C. and Short, W., editors, 2015 Geological Gems of California, California Geological Survey under Interagency Agreement C01718011 with California State Parks.

GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 45

# Picacho State Recreation Area

## Sonoran Wetlands

Several designated wilderness areas and wildlife refuges surround Picacho State Recreation Area. The wildlife refuges lie along the Colorado River, an important oasis for birds migrating along the intercontinental Pacific Flyway. The river delta lies approximately 12 river miles downstream in Mexico and provides the most significant desert estuary and wetlands in the American Southwest.

### Features:

Structural geology and tectonics of highly extended terrane, and ore deposits

The geologic history of the Sonoran desert defines a sub-province of the much larger Basin and Range geomorphic province which extends from Oregon and Idaho to Mexico. The most conspicuous aspects of this scenic geologic sub-province resulted from the Basin and Range extension. Scattered yet nationally important deposits of metallic ore that once fueled the desert economy occur near the State Recreation Area.

**Why it's important:** Picacho SRA lies on the State border along the Colorado River which crosses the thirsty Sonoran Desert. The SRA characterizes the topography and geology of eastern California's Mojave Desert Geomorphic Province which overlaps with the Sonoran Desert. This geologic landscape is continuous throughout southern Arizona—home of the northern Sonoran Desert.

## Mining

The Picacho District is distinguished as the home of the earliest recorded gold mining in California starting sporadically in 1779. Gold was mined from Bear Canyon and along Picacho Road as well as other areas surrounding the SRA. Other metals (silver, lead, and copper) were mined but were less economically important. Within Copper Basin, just south of the SRA, low grade copper deposits can be recognized by a greenish-blue coloration. Ore was likely hauled through the SRA to the mill. The mill site along the river is preserved within the SRA. Paddlewheel boats were used to navigate the shallow waters of the river and to deliver supplies prior to the establishment of the railroad.

## Geologic Setting

Picacho State Recreation Area lies at the eastern end of the Chocolate Mountains of California that extend 100 miles toward the northwest—nearly to Joshua Tree National Monument. South and west of the Chocolate Mountains, lies the San Andreas Fault and the Salton Trough—an active rift zone within the adjacent Colorado Desert Geomorphic Province named for the lower Colorado River. The Chocolate Mountains consist of a 100-mile long fold or bulge (called an anticlinorium). The core of the anticlinorium consists of metamorphic rocks. Layers of pre-Tertiary sedimentary rocks and Tertiary (2 to 65 million years old) volcanic rocks overlay the core. The core is exposed where the volcanic and sedimentary layers have been eroded away. Faults divide the core and the cover. Due to the folding, the sedimentary and volcanic strata on the northeastern flanks of the anticlinorium generally tilt to the northeast (as in the SRA) while strata on the southwestern flanks tilt to the southwest. One of the tilted volcanic deposits occurs just south of the Picacho Mill site along Ferguson Wash and has been determined to be 26 million years old. Folding—commonly related to compression—at this time represents a paradox because the entire Basin and Range province was undergoing major extension during the mid-Tertiary.

The exposed metamorphic rocks that comprise the core of the anticlinorium range in age from millions to billions of years old. An important metamorphic rock within the SRA is the schist which is generally thought to correlate with other schists in the region that formed in the Late Cretaceous (65-100 million years ago). These regionally extensive schists are collectively referred to as the Pelona-Orocopia-Rand schists (POR schists). The POR schists are isolated bodies of pervasively metamorphosed and deformed sandstone, stretching across southern California and into southwestern Arizona. They probably formed 20 miles deep above a subduction zone. Some geologists suggest these deposits correlate to the Franciscan Formation (in northern California's Coast Ranges).

## Mid-Tertiary

The mid-Tertiary (37 to 15 million years ago) marks an important change in the way the North American and Pacific tectonic plates converged. As a result, the rate of subduction slowed and magma began to rise in the crust feeding a series of magma chambers and volcanoes that erupted across the region. At the same time, changes in the stress pattern stretched the crust (as much as 100%) westward. This stretching, or extension, broke the crust into a series of tilted fault blocks and basins giving the Basin and Range Province its name. In areas, the extension exposed the basement metamorphic rocks along a meshwork of faults.

## Colorado River

Prior to the mid-Tertiary, much of this region was topographically higher than the Colorado Plateau and drainage was to the north. But between 8 and 14 million years ago, this situation reversed, as the Colorado Plateau uplifted and the Basin and Range stretched. Drainage eventually re-organized to flow southward. The river that begins in Colorado established itself through the Grand Canyon and in the local area within the past five million years. Prior to construction of several dams, the natural flow of the Colorado River was highly erratic. Draining a large area of the erodible continental interior, it carried a very heavy load of sediment, which was ultimately flushed out into the delta at the head of the Sea of Cortez. Now, the dams trap much of the sediment and water. The riparian zone and estuary near and downstream of Picacho once supported vast wetlands, much of which have since been converted to agriculture. Within the State Recreation Area, abandoned channels (Taylor Lake and Stewart's Lake) and nearby wildlife refuges preserve some of the natural values of the river.

> **The riparian zone and estuary near and downstream of the SRA once supported vast wetlands ...**

## Final Thoughts

Gold prospecting has been a catalyst for geologic study since before California's statehood.

*Written by Mike Fuller, California Geological Survey*
*Photos: John Mistchenko*

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# Peninsular Ranges Geomorphic Province

The Peninsular Ranges geomorphic province consists of a series of mountain ranges separated by long valleys, formed from faults branching from the San Andreas Fault. The topographic trend is similar to the Coast Ranges, but the geology is more like the Sierra Nevada, with granitic rocks intruding the older metamorphic rocks. The Los Angeles Basin and the Channel Islands of Santa Catalina, Santa Barbara, San Clemente and San Nicolas are included in this province. Also included is the surrounding continental shelf (cut by deep submarine fault troughs). At the northern end of the province Mount San Jacinto forms the dramatic backdrop to the Coachella Valley more than 10,000 feet below. The Peninsular Ranges extend south across the international border into Baja California, forming the spine of Baja California.

## Tectonic Setting

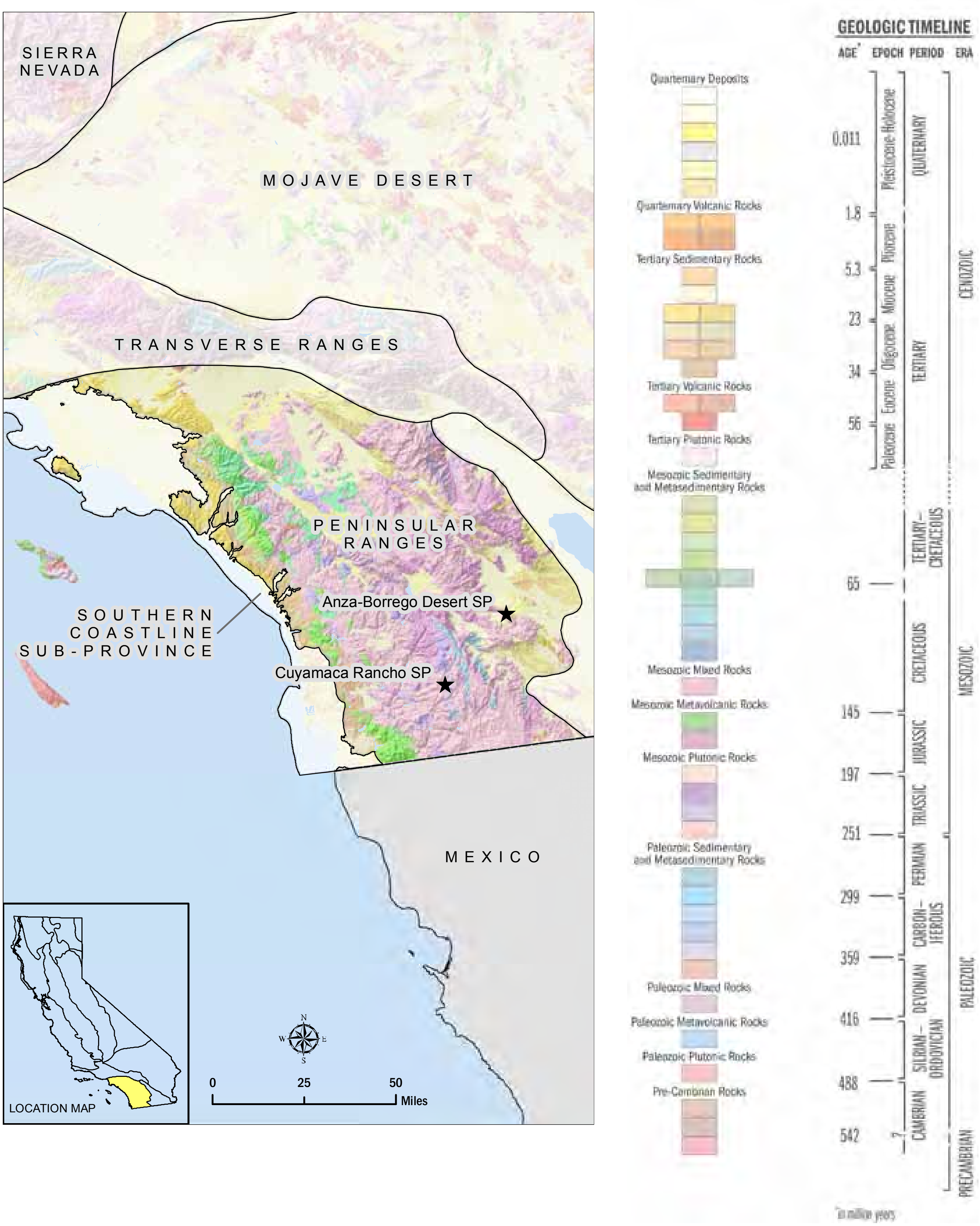
The Peninsular Ranges and the very similar Sierra Nevada probably formed in similar tectonic environments during the same period of time. However, they currently lie on opposite sides of the tectonic plate boundary represented by the San Andreas Fault system. The Peninsular Ranges are slowly moving northward along the coast headed toward Alaska.

## GeoGems

**San Onofre State Beach, Torrey Pines State Natural Reserve,** and **Cuyamaca Rancho State Park** lie within the Peninsular Ranges geomorphic province. Cuyamaca Rancho State Park is the most representative of the Peninsular Ranges, whereas Torrey Pines and San Onofre are examples of the Southern Coastline Geomorphic Subprovince described in GeoGem Note 50. **Anza-Borrego Desert State Park** spans the boundary between the Peninsular Ranges and the Colorado Desert geomorphic province. The northwestern portions of Anza-Borrego Desert State Park are very representative of the Peninsular Ranges geomorphic province.

*Written by Mike Fuller and others, California Geological Survey*
*Photos: Mike Fuller*

## Simplified Geologic Map | Peninsular Range Geomorphic Province



## NOTES:

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# Anza-Borrego Desert State Park

National Natural Landmark 1974

## Twisted and Broken

In addition to lying along the boundary between the North American and Pacific tectonic plates, Anza-Borrego Desert State Park occupies a large portion of the eastern Peninsular Ranges geomorphic province. It actually occurs in the boundary zone with the Colorado Desert Geomorphic Province. The two provinces interfinger with each other. The rocks from each province mutually overlap and mix as the boundary adjusts one way or the other. The mountains belong to the Peninsula Ranges Province, while the valleys belong to the other. The boundary is a collection of faults which are planes along which rocks on either side are shuffled. In the park, there has been much redistribution of rocks. Boundary adjustments are illustrated by progressive changes in activity along the various faults. This complexity is a side-effect of a more profound, much larger scale boundary between the two tectonic plates which grind past another at rate of ~35 mm/year.

**Feature(s):**

Earthquake deformation

**Why it's important:** Anza-Borrego Desert State Park is a great park to observe fault features and studying earthquake hazards, due to the relative lack of vegetation and development, its large size, and its location along the tectonic plate boundary. Both the Elsinore and San Jacinto Faults cut through the park. Historic accounts of earthquakes in this region are readily available but only date back several decades. One way to discern the longer history of earthquakes is to view how segments of faults have disrupted the topography. Scars from past earthquakes often form abrupt vertical steps (scarps) in the landscape. When fault scarps cut across youthful geomorphic features such as alluvial fans and dried lake (playa) deposits, we can deduce that the earthquakes that produced the scarps occurred sometime after deposition. Many of the alluvial fan surfaces and playa deposits are less than several thousand years old. In the park, there are several locales where fresh faults scarps can be seen.

Throughout most of California, the San Andreas Fault functions as the boundary (suture) between the North American plate and the Pacific plate; that is, rocks west of the fault actually are passengers of the northwesterly bound Pacific plate. The boundary splits into several roughly parallel fault zones south of the Transverse Ranges—the San Andreas proper, the San Jacinto, and the Elsinore Faults. The San Andreas proper lies to the east of the park and runs along the eastern shore of the Salton Sea. The Elsinore and San Jacinto Faults cut through the park and split into several strands. Consequently, the plate boundary becomes a 100-mile-wide boundary zone south of the Transverse Ranges with the Salton Sea as its centerpiece. The sea occupies a sunken area in a large rift zone known as the Salton Trough. The water level in the Salton Sea is currently 245 feet below sea level but 300 to 500 years ago it was 42 feet above sea level and inundated portions of the park.

**What you can see:** Fault scarps across fans and lakebeds, truncated or notched ridges.

## San Jacinto Fault Zone

This fault zone is of considerable interest to earth scientists. The San Jacinto Fault zone is composed of discrete yet related branches known as the Coyote Creek, Buck Ridge, Clark, San Felipe, Superstition Hills, and Superstition Mountain Faults. Each branch is very active and capable of producing strong earthquakes. Recent local, moderate magnitude quakes occurred at Arroyo Salado (1954), Borrego Mountain (1968), and Superstition Hills (1987).

Evidence of recent faulting and change can be read in the faceted spurs along Coyote Mountain and east of Clark Valley on the west face of the Santa Rosa Mountains. Well-preserved fault-scarps, offset drainages, sags, shutter and pressure ridges, aligned valleys, and offset alluvial fans testify to the recent vertical and lateral land movement.

## Elsinore Fault Zone

In Anza-Borrego, the Elsinore Fault zone is comprised of the following faults: Agua Tibia-Earthquake Valley, San Felipe, Tierra Blanca Mountains Frontal, and Vallecito Creek faults. Each of these is capable of generating a major earthquake. The impressive

**During the 1892 Laguna Salada quake, the western edge of the sediment-filled Vallecito-Fish Creek Basin dropped by as much as 20 feet.**

landscape along County Highway S-2 through the Carrizo Corridor is a result of the combined tectonic movements of these faults. South of the international border, the Elsinore Fault zone's continuation is the Laguna Salada Fault, which was responsible for the 1892 quake that caused considerable alarm in the San Diego area, cracking large buildings and causing landslides. That quake produced an impressive fault scarp through southern Anza-Borrego. Its 12-feet vertical fault scarp rivals well-known escarpments along the eastern Panamint Mountains in Death Valley, the Lone Pine fault escarpment in the Alabama Hills of Owens Valley, and the Hilton Creek fault scarp south of Mammoth Lakes in the eastern Sierra Nevada.

The Tierra Blanca Mountains Frontal Fault is prominent between Agua Caliente County Park and Bow Willow. It separates the Fish Creek Mountain tilt-block from the Tierra Blanca Mountains. During the 1892 Laguna Salada quake, the western edge of the sediment-filled Vallecito-Fish Creek Basin dropped by as much as 20 feet.

## Final Thoughts

Earthquakes are a part of nature's grand process that continually molds and shapes the fragile crust of Anza-Borrego. Although these complex fault processes may appear dormant, occasionally they lurch dramatically. Many of the iconic desert features such as hot springs, badlands, palm canyons, sand dunes, arroyos, and desert peaks are the result of ongoing geologic construction.

*Written by Paul Remeika,California State Parks (retired)*
*and Mike Fuller, California Geological Survey*
*Photos: Jeremy Lancaster*

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# Anza-Borrego Desert State Park

National Natural Landmark 1974

Photo: MIke Fuller

## Canyon Cutting

The mountain fronts along the western side of Anza-Borrego Desert State Park consist of a sequence of parallel canyons and arroyos. Some canyons are visually dramatic and easy to see: Henderson, Borrego-Palm, and Hellhole. Each owes its existence to catastrophic and episodic erosion by running water, which removes rock debris from high ground and deposits it along valley margins and in low desert flood basins. Few canyons sustain a year-round stream. Most remain dry, draining occasional snow melt from high, forested ridges.

**Feature(s):**

Erosion, canyons, and alluvial fans

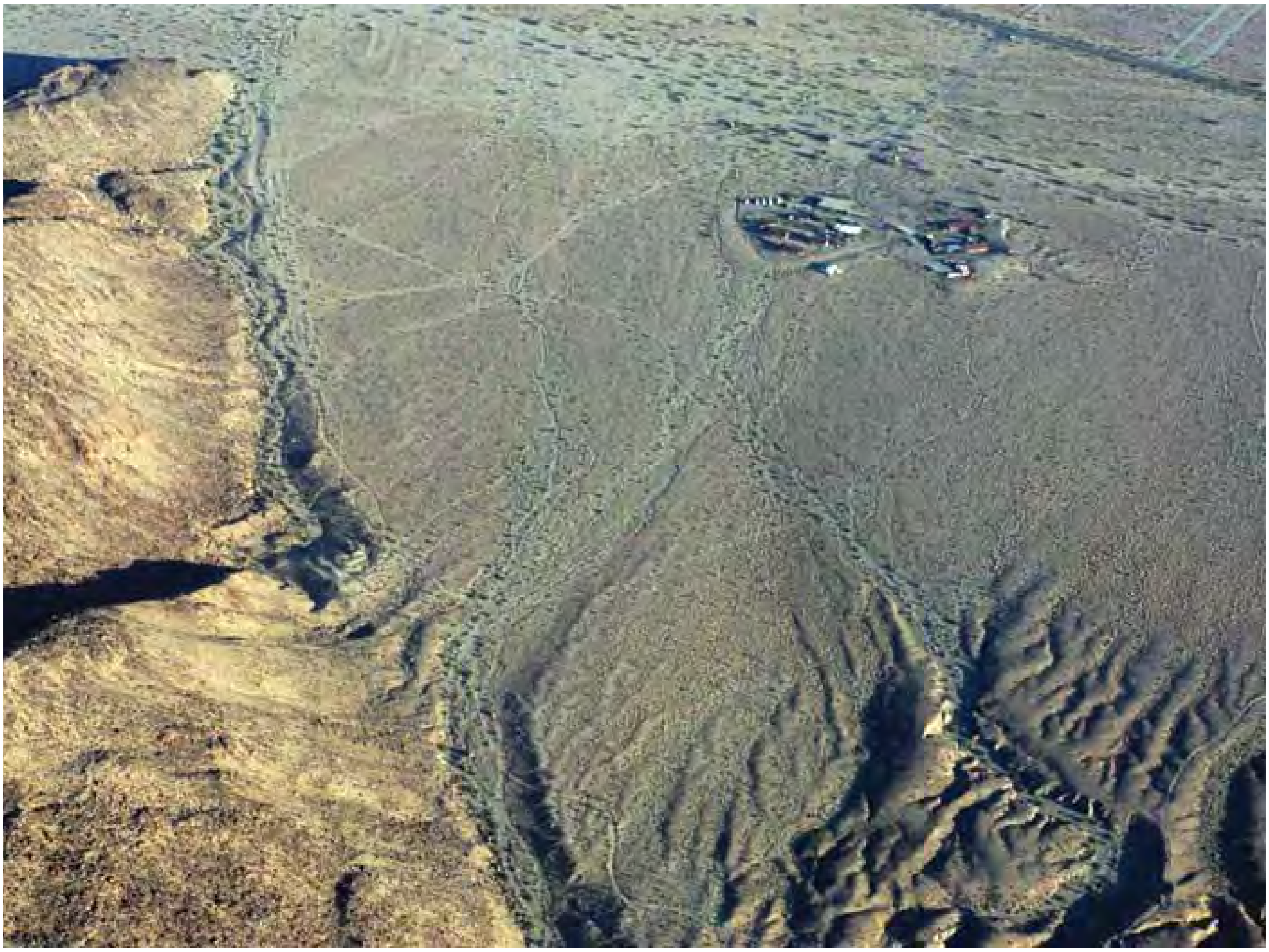
Borrego-Palm Canyon is tucked between the monolithic walls of Indianhead and San Ysidro Peak. A trail allows easy access to sheltered palm groves, cascading waterfalls, a gurgling brook, and whorls of polished crystalline rock.

**Why it's important:** Anza-Borrego's rugged landscape formed largely by the forces of erosion attacking the uplifted mountains. The higher the mountains rise, the more vigorously they are attacked by rain, snow, ice, and wind, as they yield to the constant pull of gravity. Weathering and erosion slowly wear down peaks and cliffs to produce huge volumes of sediment.

The sediment moves through canyons and washes, onto expansive alluvial fans at the base of the mountain slopes, mouths of canyons, and onto basin floors. Often this occurs in large pulses carried by dangerous flash floods.

The placid brook in Borrego-Palm Canyon may seem incapable of carving through several thousand feet of rock; however, when occasional rains strike, they can inundate the desert canyons in flash floods. Such sudden and heavy rainstorms occurred on September 10, 1976 during Hurricane Kathleen, between August 16 and 17, 1977 during Hurricane Doreen, and between February 27 and March 1, 1990 during a major winter storm.

The most recent flash flood event occurred on the afternoon of September 10, 2004. Runoff soon funneled down every crack and crevice, purging side canyons of debris and rubble in rills, then rivulets, building and gathering momentum as sediment-choked torrents. The narrow canyon acted as a sluice for the rushing water. The flash flood waters flooded half the campground and employee residences, and littered the desert floor with mud, debris, boulders, and palm trunks as far east as the de Anza country club and golf course. Neighborhoods surrounded by the park were submerged in a blanket of gooey mud over two feet thick. The waters carried huge boulders out onto the alluvial fan, followed by cobbles, then pebbles, sand, silt, and mud farther from the canyon mouth. The smaller the fragment, the farther it was carried out onto the alluvial fan or into the basin.



## Alluvial Fans

Alluvial fans form where steep, confined mountain streams flow out (debouch) onto a valley floor. They consist of sand, gravel, and boulders deposited during myriad flood events. These flood flows are thick with debris eroded from the mountains and canyons. The debris largely consists of mud, rocks, and vegetation. Depositional patterns are characterized by a distributary system of channels that convey flood waters and sediment onto the fan surface.

Major fans occur at the mouths of Coyote, Henderson, Borrego-Palm, and Hellhole Canyons along the western edge of Borrego Valley. These delta-shaped outwash plains radiate from an apex where the stream channel emerges from the canyon. The coarsest and thickest deposits occur near the mouth and include a variety of boulders and cobbles. Gravelly sands, sand, silt, and clay occur immediately down-gradient, representing sheet flood deposits more distant from the canyon mouth. If fine-grained sediments reach the basin floor, they contribute to playa deposits of mud and silt. Good examples of this can be seen in Borrego Sink and Clark Dry Lake.

On unconfined alluvial fan surfaces, drainages become choked with alluvium and begin to level out. Streams will eventually breach their own levees to seek steeper gradients with less resistance. Shifting from side to side, they eventually re-distribute their sediments like a windshield wiper, back and forth. Flash flood waters tend to maintain fan symmetry over time, building up the alluvial fan.

Fans expand with repeated outpourings of debris, spreading so extensively that they may coalesce laterally along a mountain front. Such a merger is called a “bajada.” Connecting older mountain canyons to desert floor, bajadas are temporary storage for sediments en route to the basins. Youthful mountain canyons are short and steep, and have isolated alluvial fan cones growing along their western bases. The lower ends of the fan cones interfinger with finer-grained playa sediments collected in the actively subsiding basin of Clark Dry Lake or interfinger with sand deposits emanating from Rockhouse Canyon. Uplift has been so recent that erosion has had little time to modify the face of the mountain fronts.

In the southern area of the state park, faults that parallel mountain ranges have elevated the older fans, rejuvenating their channel gradients. Streams entrench into these earlier deposits, and build up a staircase of new alluvial cones basinward. Such features occur along the Tierra Blanca Mountains north and south of the small town of Canebrake along the Tierra Blanca Mountains Frontal Fault, and on the northern side of San Felipe Creek west of Tamarisk Grove along the San Felipe Fault.

## Final Thoughts

Flood by flood, deposition is the last chapter of the erosion cycle. Sediments transported downstream eventually collect in low-lying desert basins without external drainages—Borrego Sink, Clark Dry Lake, or the Salton Basin. These comparatively young structural depressions are filled with thousands of feet of interbedded silt and clay playa deposits.

*Written by Paul Remeika, California State Parks (retired)*
*Photos: Jeremy Lancaster*

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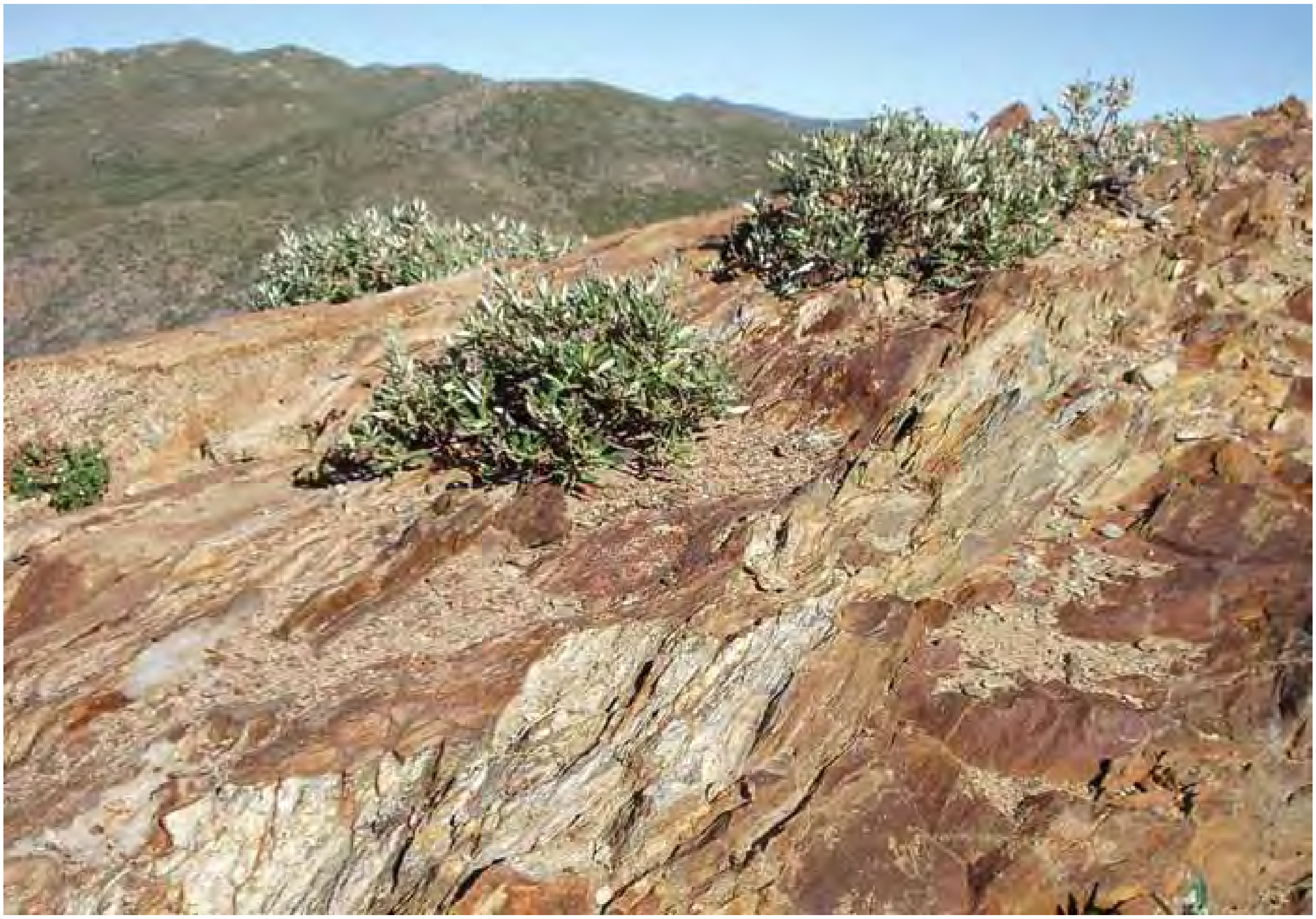
# Cuyamaca Rancho State Park



## Peninsular Ranges Batholith

**Features/Process:**

Petrology of the roots of ancient mountains on an exotic terrane along the plate boundary

The Cuyamaca Rancho State Park lies within the Peninsular Ranges geomorphic province of southern California, which is characterized by a series of northwest trending mountains and valleys that are similar in trend to the San Andreas Fault system that lies to the east. The Peninsular Ranges are chiefly made up of coarsely crystalline igneous rock, termed the Peninsular Ranges Batholith. The events that formed the batholith are complex, but clues to its formation can be gathered from an analysis of geology of the park and surrounding region.

Without question, it is the grinding of the North American plate sliding past the Pacific plate known as the San Andreas Fault system that is currently controlling the landforms of the region. But this has been occurring for a relatively brief period

**Why it's important:**

The rounded hills of granitic and metamorphic rock of the Peninsular Ranges are the deep roots of a much different ancient range that included volcanoes and high mountains possibly like the Andes. By examining these roots, we learn about the internal workings of other mountains.

of geologic time. Before this fault started to rip the state apart, California was the scene of a major mountain building events, which occurred during the Mesozoic era. These mountain building events, known as the Nevadan and Sevier Orogenies, were the result of the collision and subduction of the Farallon oceanic plate beneath the North American continental plate. A modern analogy to this event is that of the Andes Mountains of South America. There, the Andes are constructed of active and inactive volcanoes fed from magma due to the subduction of the Nazca oceanic plate below the South American continental plate.

The geologic record of these mountain building events is evident in the Cuyamaca Rancho State Park area as the Triassic-Jurassic Julian Schist, and the Jurassic and Cretaceous metamorphic and igneous rocks. The following sections discuss those rocks and the implications to the formation of the batholith.

## Mountain-Building Events and the Rock Record

Around 165 million years ago, during the Jurassic Period of the Mesozoic Era, the west coast of North America was being subjected to intense volcanic activity. The supercontinent Pangaea was breaking apart and the North American plate was carrying the continent toward the west as it still does today. The Pacific Ocean floor (oceanic crust) broke into several plates, including the Farallon plate, and was pushed under North America. The subducted plates melted at depth beneath the continental margin. Southern California was in a different geographic location, off the coast of the current Mexican mainland and submerged. Many volcanoes formed far to the east

**What you can see:** A series of granitic and metamorphosed sedimentary rocks that represent past mountain building events.

along the western margin of the continent creating a volcanic island arc. Sediment and volcanic rocks eroded from the volcanic highlands to the east were deposited in the ocean basins to the west.

Further volcanism occurred later in two pulses during the Cretaceous period, which possibly consisted of volcanic islands being formed offshore, where magma erupted and cooled into andesite and basalt. As the continuing plate collision occurred along the western margin, the island volcanoes were moved east and shoved up against the North American continent. The resulting collision compressed and squeezed existing igneous and sedimentary rocks, causing them to be metamorphosed. The constant compression also caused them to be pushed up into huge mountains. Since then, the great mountains have been eroded to their cores.

## What Rocks Can Be Seen?

During the mountain building events, volcanoes generated abundant quantities of volcanic rocks. However, these were not the only rocks that were deposited. As some of the magma was trapped below the volcanoes, it cooled beneath miles of overlying rock and sediment. These masses of rock that cooled deep in the earth’s crust are Jurassic granodiorite, Cretaceous gabbro and Cretaceous monzogranite. These rocks, along with other similar “granitic” rocks, form the Peninsular Ranges Batholith. The Jurassic rocks are the cores of the ancient volcanoes, and the remnants of sand, mud and volcanic debris deposited in the ocean basins. These rocks appear layered or banded because they were subject to immense heat and pressure causing the minerals to orient themselves in response to the pressure.

Some of the Cretaceous rocks in the park area also represent the cores of ancient volcanoes, but a slightly different type. The Cretaceous Cuyamaca gabbro, a dark crystalline rock, has been interpreted to be the core of an island volcanic system. The Chiquito Peak monzogranite is much lighter in color and was emplaced around the time of the gabbro, and may represent the partial melting of the continental crust as the magma and island arc system slammed into the North American continent. The Cuyamaca gabbro and Chiquito Peak monzogranite can be observed in the vicinity of the Cuyamaca Rancho State Park Interpretive Center.

## Final Thoughts

As a fragment of continent caught on the oceanic plate heading northward toward Alaska, this exotic terrane will undergo many more profound changes. Will it ever make it there before erosion obliterates all vestiges?

*Written by Jeremy Lancaster, California Geological Survey*
*Photos: Janis Hernandez*

GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 50

# Southern Coastline Geomorphic Sub-Province

Photo: Pam Irvine

Essentially, the coastline itself qualifies as a distinct geomorphic province evenly divided between north and south. Because the coastline is 1,100 miles long, the climate and water temperatures in the south are more mild than in the north. The flora and fauna vary accordingly. The California coastline is another dynamic boundary zone, of varying width, where geologic forces collide. Coastal landforms include beaches, dunes, tide pools, estuaries, lagoons, steep cliffs, marine terraces, and sea stacks.

The coastline can be subdivided into two sections. The northern section runs the length of the Coast Ranges province; the southern runs along the western edge of the provinces of the Transverse Ranges and the Peninsular Ranges. Along the southern section, the coastal geomorphology is superimposed on the landforms of the Transverse Ranges and Peninsular Ranges geomorphic provinces. The southern coastline trends northwestwardly from San Diego to Point Conception. Due to the orientation, the southern shores are somewhat sheltered from storms that arrive from the west and northwest. A broad continental shelf lies along the southern section. The shallow offshore shelf helps absorb wave energy by causing waves to break further from shore. Sand deposition started roughly 10,000 years ago and is relatively widespread along the southern coast, creating the state's popular beaches.

Photo: Mike Fuller

The position of the shoreline is directly related to sea level and land elevation, both of which are variable through time. Sea level was as much as 400 feet lower during the last Ice Age because so much water was trapped as ice on the glaciers that covered northern and southern latitudes. During this time the shoreline position was as much as several miles west of its current location extending toward the Channel Islands. During the Ice Ages, major rivers cut deep canyons into the continental shelf, creating submarine canyons. During the last interglacial, sea level was approximately 15 to 20 feet higher and coastal wetlands and estuaries were correspondingly much more extensive than they are today.

## Tectonic Setting

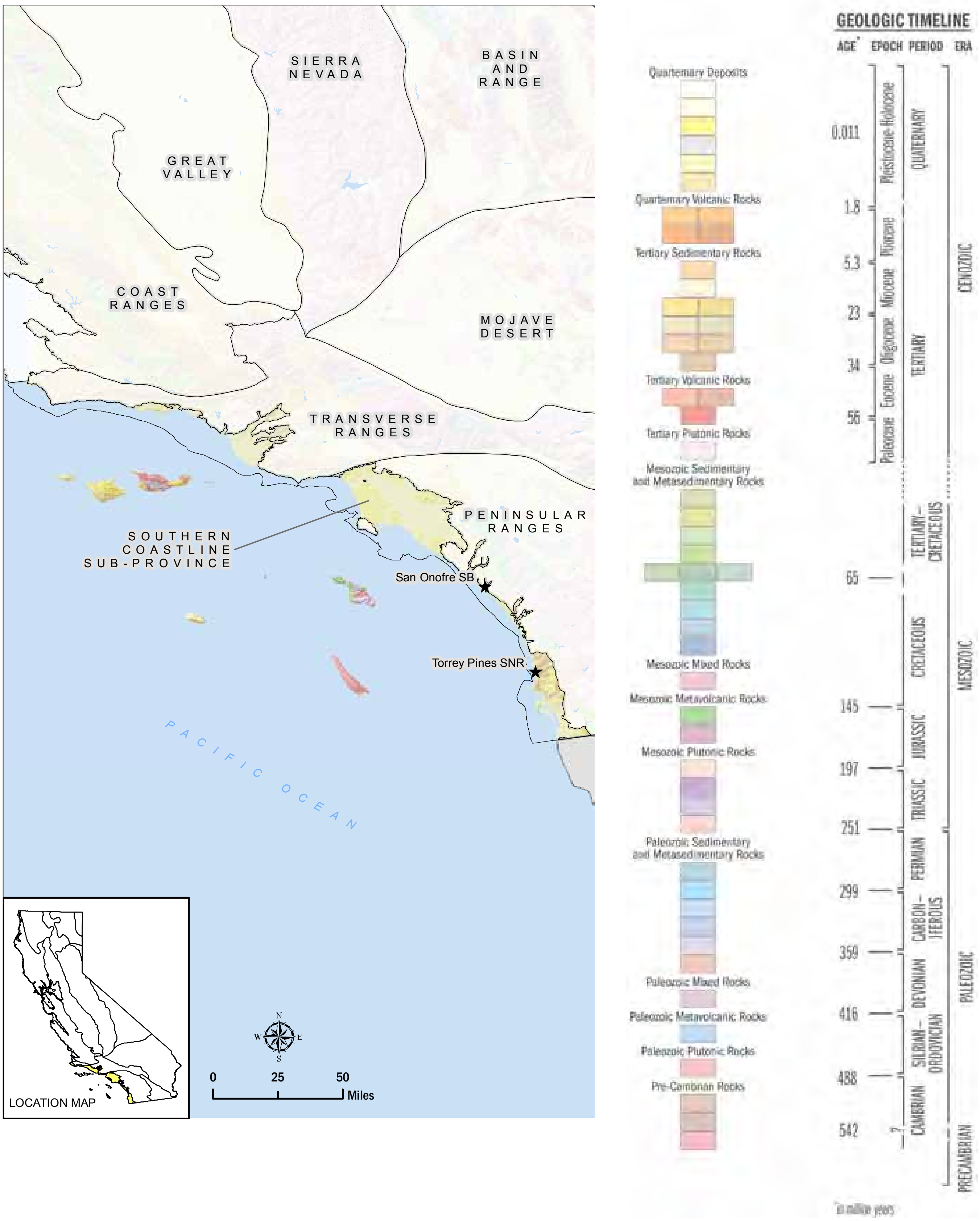
Portions of the coast have been uplifted due to tectonic forces, while others have subsided. The interplay of uplift and sea level fluctuations produced numerous marine terraces all along the coast. The highest terraces can extend several miles inland to what was once the shoreline. Subsidence along with sea level rise since the end of the last Ice Age has drowned river mouths. This moved the shoreline inland. Such a dynamic setting have produced a long list of landscapes and features including: accreted terranes, marine terraces, islands, sea stacks, dunes, beaches, and concretions.

## GeoGems

Three GeoGems that lie along the southern coast are **Gaviota State Park, San Onofre State Beach,** and **Torrey Pines State Natural Reserve**. However, for our purposes, Gaviota State Park has been selected as a representative of the Transverse Ranges geomorphic province.

*Written by Mike Fuller, California Geological Survey*

## Simplified Geologic Map | Southern Coastline Sub-Province



**NOTES:**

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# Torrey Pines SB and Torrey Pines SNR

National Natural Landmark 1977 | State Beach and State Natural Reserve

## Crumbling Cliffs

**Features/Processes:** Coastal geomorphology and geobotany, with concretions and fossils

Along the beachfront in the southern reserve area, a dramatic cliff face towers over the Pacific Ocean. This cliff face exposes a thick stack of sedimentary rocks that span a great period of time from Middle Eocene (roughly 49 million years before present) to the Pleistocene (120,000 years ago). Eocene deposits are relatively rare throughout the west and so these deposits help fill a huge knowledge gap in the geologic record. The rocks in the sea cliffs represent a former bay that was uplifted long ago. They also reveal where the ocean invaded the land, producing a similar environment to what today exists between the sandy beach and Los Peñasquitos Marsh Natural Preserve to the east.

**Why it's important:** Torrey Pines State Natural Reserve preserves habitat for North America's rarest and most geographically restricted pine tree species. Several natural processes interact to form the habitat for the pines. The reserve and beach are perfect places for visitors to see vestiges of past environments and their continuing influence on the landscape and to envision the dynamics of shoreline processes.

The pines prefer the sandy soils on the coastal bluffs and ravines within the Reserve. The pines were once more widespread during a different climate regime. Another population of Torrey Pine exists in two small groves on Santa Catalina Island. These populations of rare pines are thought to be hold-outs from the Ice Ages. They are literally losing precious ground to rapid erosion of the sandy slopes they occupy.

These cliffs of sedimentary rocks are relatively weak and prone to landslides especially as they are attacked and undercut along the beach by waves. Although a hazard, landslides replenish the beaches with new sand. While a slumped mass remains on the beach, it buffers the steep cliff from wave attack. The waves sweep away the mass and again attack the cliffs eventually triggering another landslide. The sand is carried into a current called the Oceanside Littoral Cell. Researchers estimate that about half of the natural sand load in the Oceanside Littoral Cell has been eliminated due to the construction of dams, the loss from gravel mining, and the urbanization of southern California. This has resulted in accelerated beach loss (and in places accelerated bluff retreat) along the affected coastline.

**What you can see:** Majestic, towering sea cliffs sliced by ocean wave erosion and hammered by pounding waves. The Torrey Sandstone and underlying Del Mar Formation comprise the majority of the sea cliff edifice; the Quaternary marine terraces on top were deposited after tens of millions of years of erosion. The sea cliffs reveal beautiful shapes and patterns of soft sediment deformation, formed when the sands were below sea level and saturated with water. A gigantic landslide south of Flat Rock deformed the cliff into a stair-step like shape. Marble-sized iron oxide concretions mantle some of the terrace surfaces.

## The Embayment

During the Eocene, a great embayment of the Pacific Ocean into the North American continent existed from Carlsbad in the north, to Baja in the south, and east beyond Poway. Sediments of the Del Mar Formation and Torrey Sandstone deposited in this embayment. The Del Mar Formation is yellowish-green claystone that formed in a lagoon-like environment similar to, but much larger than, the Los Penasquitos lagoon. Near the top of the Del Mar in the vicinity of Flat Rock is a layer of fossilized oyster shells called a “coquina.” The Torrey Sandstone is light brown sandstone that likely formed as a barrier beach west of a lagoon. The sand barrier in front of the Los Penasquitos Lagoon provides a small example.

What we see today in map view is that the lagoon and the sand spit are adjacent to each other. However, in the cliff face at Razor Point is something entirely different. The two rock types, yellowish-green claystone (Del Mar Formation), and light brown sandstone (Torrey Sandstone), are actually stacked on top of, but not adjacent to each other. What does this mean? This can be explained by understanding how deposits proceed inland as ocean level rises relative to a land mass. Geologists call this a transgression, when sea level rose and the beach front and lagoon both migrated inland. The two strata were deposited simultaneously, yet if you cut a vertical cliff face into them you see the older lagoon deposits under the younger beach sand deposits.

Much has happened since then. The fine-grained sediment deposited in the lagoon and the sands deposited along the barrier beaches have undergone lithification. This means that they have turned into rock, as the original air and water was pressed out and the sediment was squeezed by overlying deposits under the force of gravity.

Since Eocene time, sea level has risen and fallen many times and other rocks in the area record these events. During one highstand approximately 700,000 years ago, the sea cut a marine terrace into the Torrey Sandstone upon which the Linda Vista Formation was deposited. The Linda Vista is a distinctive, rusted color sandstone, with abundant marble- and pea-sized iron stones.

Along the coastal bluffs at Razor Point, a much younger deposit called the Bay Point Formation rests on top of the Linda Vista Formation. This deposit was laid down during a period when the glaciers had mostly melted, and sea level had risen. This period is called the Sangamon interglacial and it started roughly 120,000 years before present. The Bay Point Formation contains marine fossils at its base, but gradually becomes terrestrial (or dry land) sandy deposits near the top. Because the Bay Point Formation is roughly 48 million years younger than the Eocene rocks on which it rests, it erodes differently and has a characteristic red hue due to weathering and oxidation of iron and magnesium-bearing minerals. Because of its youthful age, it has not yet consolidated and turned to rock, so it erodes by rilling and forms badland topography.

## Final Thoughts

The shoreline cliffs at Torrey Pines both provide solitude from the nearby urban environment and reveal a unique chapter of the geologic past that lies beneath the metropolis of San Diego.

*Written by Jeremy Lancaster, California Geological Survey*
*Photos: Mike Fuller*

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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 52

# San Onofre State Beach

## Frontline in the Battle of Land and Sea

The coastline represents the cutting edge of the ocean where it attacks the edge of the continent. As the waves advance, the shoreline is said to retreat. The cutting of the land forms sea cliffs and landslides and produces great quantities of sand to form the broad beach. Softer rocks are cut away more easily than harder materials. Much of the geologic formations at San Onofre State Beach are relatively soft and easily eroded sedimentary rocks. This soft material was deposited 20 million years ago, when this entire region was part of the seafloor. Then the continental margin was many miles to the east. The older sediments that ultimately became these rocks were deposited in deep marine basins and subsequently uplifted to form a large bay. Sediments

### Feature/Process:

Seismic and coastal geologic hazards, with landslides and barrancas

**What you can see:** Dramatic exposure of the Cristianitos fault (between San Onofre Nuclear Generating Station and Echo Arch); the Echo Arch landslide; and gigantic gullies (barrancas) that cut through the flat-lying terrace deposits.

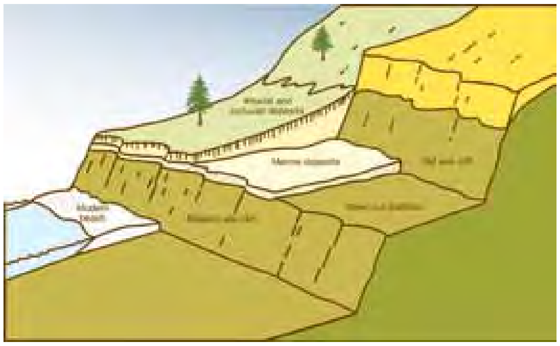
accumulated in the bay. Wave action planed off the surface creating the relatively flat terraces. Continued uplift (averaging about three inches every thousand years) elevated the terraces and the sedimentary rocks to their present position where waves attack the base of the soft slopes.

Although erosion and shoreline retreat are rapid due to the softness of the rock, other factors such as land-use and climate also play important roles. For example, during especially wet periods with intense rainfall, landslides are very common along these slopes. Portions of the bluffs are retreating at a rate of six feet per year. Another conspicuous example of the role of land-use on geology is the development of widespread erosion caused by changes in the natural drainage patterns that resulted from road construction. Along the edge of the dominant terrace, extensive, deep gullies known as barrancas developed. Pre-existing drainages deepened and new drainages formed at the outlets of drainage devices along the interstate.

**Why it's important:** San Onofre State Beach exemplifies the joys and challenges of living on the fragile coast. The scenic beauty derives from the panoply of geologic processes, many of which can be hazardous and difficult to manage. Landslides, massive erosion, and earthquakes are the results of a long geologic history that is readily on display within the park.

## Marine Terraces

San Onofre State Beach is an excellent place to view the dynamics of a migrating coastline. The 12 marine terraces record the relative rise and fall and lateral migration of the coastline. Just in the last 125,000 years, the location of the coastline has been as far east as the back edge of the broad, dominant marine terrace. In fact, the highest terrace records the easternmost extent during the Pleistocene. Conversely, during the lowest sea level, when water was trapped in glaciers worldwide, the shoreline was far to the west. The lowest recognized terrace occurs 250 feet below sea level; while the highest is 1,250 feet above sea level. Each terrace formed at a different relative sea level.



**Marine terraces** consist of a wave-cut bedrock platform (bench) with a thin, discontinuous blanket of marine and younger non-marine deposits. The origins of the terraces are tied to changes in climate and associated fluctuations in eustatic (worldwide) sea level during the Pleistocene epoch 11,000-1.1 million years ago. Modified from Weber and Allwardt, 2001.

Echo Arch Campground is a great observation area to appreciate the significance of landslides and a cross-section of the former terrace. North of the Echo Arch campground, one can observe the sharp contrast in color along the bluff approximately 40 feet above the beach. The pale yellow-brown rock exposed on the bottom of the cliff face and the dark reddish-brown material on top have very different ages. In fact, the light rock was deposited on the ocean floor in the Early Pliocene Epoch (approximately five million years ago). Those sediments were buried, compressed and lithified. Then the rocks that we now call the San Mateo Formation were uplifted to near sea level approximately 125,000 years ago—based on fossil evidence. If one looks closely, a layer of boulders—the interface of the two layers—is apparent. This layer represents the sand and gravel deposited on the beach as the waves eroded the San Mateo Formation.

## Landslides

The Echo Arch landslide is approximately 1,000 feet wide, measured along the coastline. Along the three mile long Bluffs Trail, approximately 80% of the bluffs show evidence of such landslides—both a natural process that replenishes the beach and a serious hazard.

## Earthquakes—Another Geologic Hazard

The Newport-Rose Canyon Fault system lies approximately ten miles offshore and is considered active and capable of producing strong earthquakes. In the park, another fault—the Cristianitos Fault—is well displayed, well-studied, and deemed inactive.

The intense shaking produced during earthquakes can liquefy saturated sediments. Recent excavations atop the neighboring marine terraces have revealed widespread evidence of liquefaction such as sand dikes and sand blows. Some of these features disturbed archeological sites whose ages are well-constrained. The causative earthquake(s) likely occurred within the last several thousand years, possibly during historic time. Could the offshore Newport-Rose Canyon Fault system be responsible?

A strong offshore earthquake presents a real threat of tsunamis. Evidence of past tsunamis is found up to 300 feet above sea level in nearby coastal lagoons and estuaries.

## Final Thoughts

San Onofre State Beach owes its dramatic scenery to being in the battleground between land and sea. Barrancas, landslides, faults, tsunami deposits, and liquefaction features are the battle scars in the never-ending contest.

*Written by Jeremy Lancaster and Mike Fuller, California Geological Survey*
*Photos: Mike Fuller (except where noted)*

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# Colorado Desert Geomorphic Province

Photo: Cheryl Hayhurst

The Colorado Desert geomorphic province, between the Mojave Desert and the Peninsular Ranges geomorphic provinces, occupies a major boundary zone, the plate boundary. The province is mostly below sea level and is the on-land extension of the Gulf of California. The low-lying arid basin is occupied by the Salton Sea (surface elevation about 245 feet below sea level). Surrounding the Salton Sea are the ancient beach lines and silt deposits of extinct Lake Cahuilla. As a testament to the near-surface tectonic activity, there are several developed geothermal areas in the southern section.

The province hasn't always been so dry. The Colorado River that runs from Colorado and through the Grand Canyon has long delivered its heavy sediment load to the Gulf of California. The precise areas of sediment deposition shifted back and forth over time. Eventually the river delta became large enough to plug the Gulf and exclude the seawater from California. The seawater trapped in this province evaporated. On several occasions the lower Colorado River shifted course and sent water and sediment north of the plug instead of south. This resulted in a series of large freshwater lakes that eventually evaporated.

Photo: Mike Fuller

## Tectonic Setting

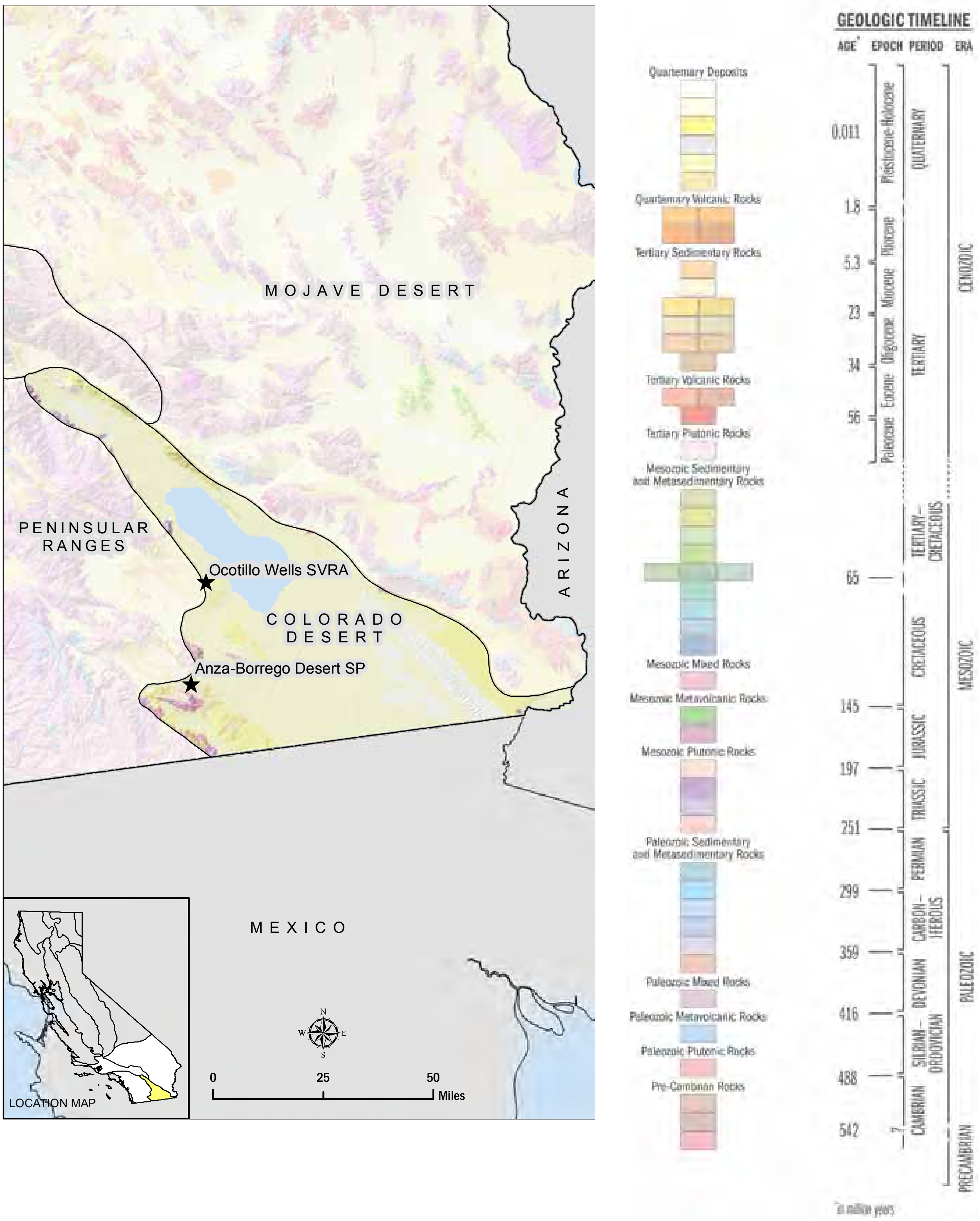
The mid-oceanic ridge runs the length of the Gulf of California and is a major rift zone between oceanic plates. Based on seismic activity, the rift appears to be advancing northward into the Colorado Desert geomorphic province. The San Andreas Fault system joins into the growing rift in very complex and confounding ways. This is one of the most seismically active places in California. The crust is so thin that geothermal energy is abundant in this very hot, parched place.

## GeoGems

Anza-Borrego, being the largest state park, provides three separate GeoGems. **Anza-Borrego Desert State Park** and **Ocotillo Wells State Vehicular Recreation Area** are the GeoGems that represent the Colorado Desert province. They lie along the province boundary with the Peninsular Ranges. Ocotillo Wells and the eastern and southern portions of Anza-Borrego consist of badlands formed in the uplifted, ancient sediments of the Colorado River. Eastern portions of Ocotillo Wells are very flat, where occupied by Lake Cahuilla only 300 years ago.

*Written by Mike Fuller and others, California Geological Survey*

## Simplified Geologic Map | Colorado Desert Geomorphic Province



## NOTES:

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# Anza-Borrego Desert State Park

## Badlands

**Feature(s):**
Badlands, fossils

The badlands at Anza-Borrego Desert State Park result from multiple phases of both erosion (easily envisioned from any of the sweeping vistas) and sediment deposition (indicated by each layer). After deposition, the sandy and silty sediments were buried under sheets of gravelly alluvium shed from the rising mountains. The gravel cap protected the underlying sediments from erosion for a period of time. Eventually the cap itself eroded, exposing the weaker underlying sediments to rapid erosion. Water is the primary agent of erosion in this parched region. Rainfall sufficient to produce erosion is relatively rare—occurring as periodic flash floods. Through time, however, the effects have become profound.

Three individual areas of badlands occur within the park: Borrego, Vallecito Creek-Fish Creek, and Carrizo Badlands. These areas represent ancient lake basins in which the sediments were deposited. The Colorado River drained a large portion of the southwestern continent, excavated the Grand Canyon, and deposited the sediments as deltas where it emptied into these basins over the last five million years. The sediments range from very fine sand to coarse gravels and have a combined thickness of 19,000 feet. To accumulate such thick deposits the basins must have been continually subsiding during deposition.

### Why it's important:

In California, badlands are an unusual and intriguing landscape. The origin of the badlands in the park is especially fascinating. It is mind-boggling to think that much of these sediments are the waste products of the Grand Canyon and Colorado River because the idea is so contrary to the current topography. Of course some of the deposits were locally derived. The river no longer runs this way. The landscape was very different when the river sediments were deposited but has changed rapidly due to widespread deformation along major faults such as the San Andreas and San Jacinto Faults.

The assemblages of fossils are very important because they compose the most complete record of the animals (fauna) and plants (flora) that existed in this region before and during the Ice Ages. The reconstructed skeletons of large creatures (megafauna) such as mammoths, giant sloths, saber toothed cats (the official State fossil), and giant bears are very impressive museum pieces. These species like so many others that once roamed the area are now extinct. The fossil record informs us of the transience of life and what to expect from geologic and environmental changes.

The Colorado River migrated significantly through time as indicated by the distribution of the badlands. To a lesser degree, earthquake movements along faults have shifted things around. Very gradually, earthquake movements have lifted the deposits to their current elevations and tilted the beds. The change from subsiding basins to uplifted basins marks a significant change in fault activity and is what geologists call "basin inversion."

The park occupies one of the most seismically active regions in the country. The multitude of earthquakes continue to uplift, fold, and re-organize the rocks and modify the landscape. Historically, strong earthquakes (magnitude 6 or more) occur on average once every five years in the vicinity. Large historic earthquakes include the Borrego Mountain (magnitude 6.6) quake in 1968. Without the earthquakes and basin inversion, the area's wealth of fossils would remain deeply buried and unknown.

**What you can see:** Because the badlands are deeply eroded and devoid of vegetation, it is easy to see the dipping layers of siltstone and sandstone. The strata contain the debris eroded from the surrounding area as well as by the Colorado River as it carved its course through the Colorado Plateau, forming canyons including the Grand Canyon, and deposited the eroded debris here between one and five million years ago. The mud hills conceal a rich assemblage of fossils, which are periodically exposed along the washes.

## Fossils

Any evidence of an organism, plant, or animal that is preserved in rocks constitutes a fossil. Identifiable fossils of known lineages can be used to date the age of the rocks in which they are found. However, fossils are imperfectly preserved and truly diagnostic features can be rare. Lineages are built from large collections of fossils, from which evolutionary patterns are deduced by paleontologists. Typically, there are many key pieces missing from fossil record. These factors illustrate the need for careful archiving, preservation, and protection of fossil resources.

These badlands contain the fossil remains of approximately 550 types of plants and animals that once lived here. The environment was quite different then. Woodlands bordered large lakes. Grasslands covered rolling hills and plains. Marine fossils occur in other rock formations within the park. Collectively, the various fossil assemblages constitute the most continuous archive of the history of life for the past seven million years in the west.

By examining the various layers of rock in the badlands, geologists identify beds that formed along rivers and in floodplains. These beds contain the most significant and abundant vertebrate fossils in the park. The beds date from just after the time (three million years ago) that the Isthmus of Panama joined North and South America. That land bridge made possible major migrations and mixing of North and South American faunas in what is called "the Great American Biotic Interchange." The park contains fossils of animals that originated from South America mixed with North American fauna including llamas, tapirs, horses, camels, the largest flying bird in the Northern hemisphere (16 foot wingspan), and a giant (five to six feet long) tortoise.

## Final Thoughts

This extreme landscape is the product of past landscapes upon which odd fauna roamed. At times, a sinking sediment basin at the mouth of Colorado River where animals were deeply buried, it has been pushed up by hidden forces into stark-looking hills that (through erosion) gradually reveal the secrets of the past.

*Written by Mike Fuller, California Geological Survey*
*Photos: Mike Fuller*

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GEOLOGICAL GEMS OF CALIFORNIA STATE PARKS | GEOGEM NOTE 55

# Ocotillo Wells SVRA

State Vehicular Recreation Area

Photo: Mike Fuller

## Springs and Oases

**Process/Feature:**

Tectonics and desert hydrogeology along the plate boundary

Ocotillo Wells State Vehicular Recreation Area contains two spring-fed palm oases (Five Palm Spring and Seventeen Palms) that provide refuge from the oftentimes intense heat. The oases stand in stark contrast to barren badlands that surround them. In the arid desert, springs provide havens that were a necessity for early human inhabitants and explorers, and remain so for wildlife. In the geothermal area of the Salton Trough, the springs are quite different. These include gas-charged mud springs and hot springs.

The scarcity of water in the park is also in stark contrast with the recent past. As recently as 300 years ago, the eastern half of the park was submerged beneath ancient Lake Cahuilla —a predecessor of the Salton Sea. Fossil oyster shells at Shell Reef indicate that even before freshwater Lake Cahuilla, the basin was submerged beneath marine waters in an extension of what is today the Gulf of California.

**Why it's important:** Major geologic forces are play at the park which is caught in a tug-of-war along the boundary between the North American and Pacific plates. As the Peninsular Ranges of southern California and Baja move to the northwest with the Pacific plate, they pull apart and tear the plate boundary along the San Jacinto Fault and the Salton Trough. The Salton Trough is a major rift zone that includes the eastern portion of the park. Within the rift, the crust is stretching and becoming thin, allowing the earth's usually deep heat to rise toward the surface. Active strands of the San Jacinto Fault system cross the western portion of the park. In 1968, the park was shaken by a moderately strong earthquake (magnitude 6.6) and the ground along San Felipe Wash cracked along a strand of the fault.

## Salton Trough

The Salton Trough extends from Palm Springs to the Gulf of California. Much of the trough is below sea level. At its deepest, the trough lies approximately 250 feet below sea level. At various times, Lake Cahuilla has filled part of the trough. Evidence of this can be seen by ancient beach lines and silt deposits that surround the Salton Sea. On the west side of the trough, uplifted sediments of the former delta of the ancestral Colorado River form badlands. The park is situated across both these austere landscapes.

The Santa Rosa Mountains dominate the horizon northwest of the park. These mountains form the easternmost reaches of the Peninsular Ranges, and consist of granitic and metamorphic rock that was pushed up as the Salton Trough subsided to below sea level.

The deposits of the Imperial Formation, exposed at Shell Reef, indicate that seawater inundated the Salton Trough during the early Pliocene (4.2 to 5.3 million years ago). The Colorado River flowed into and built its delta in the ocean-filled trough. By the mid-Pliocene (4.2 million years), the Colorado River brought so much sediment that the delta become large enough to plug the trough and dam off the ocean. The course of the river shifted back and forth across the enormous delta, at times flowing into the ocean, and during other times filling the Salton Trough with a lake of fresh water and sediments. The layers of sediments, known collectively as the Palm Springs Group, occur within the park. The latest filling formed ancient Lake Cahuilla 300 years ago and dried up before the late 1800s. The Palm Springs Group sediments are topped with more recent sediments. These sediments consist of the coarse-grained alluvium derived from the Santa Rosa Mountains, and fine-grained deposits from the ancient lake. These sedimentary deposits comprise the bulk of the geologic materials that underlie the park.

## Concretions

An eye-catching feature of the rocks of the Palm Springs Group is the numerous round concretions that weather out of some layers. Although common in the surrounding region, concretions are relatively rare sedimentary features. Pumpkin Patch hosts many cannonball sized concretions. Concretions exhibit a vast variety of shapes and sizes. They are thought to form during the process through which sediment turns to rock called lithification. For sediments to lithify, some cementing agent must circulate in solution through the deposits to bond the individual grains together into a solid mass. Calcium carbonate from circulating groundwater is a common cementing agent. Concretions form where the cementing agent preferentially accumulates and deposits around some nucleus that could be mineral grains or organic matter. Because the concretions are preferentially cemented compared to the rock that encases them, they better resist erosion and stand out against the softer matrix.

**What you can see:** Oases, concretions, fossil marine shells, historic lake bed.

## Lake Cahuilla Shoreline

The ancient shoreline of prehistoric Lake Cahuilla crosses the park and is important from a geological as well as an archeological perspective. The shoreline roughly coincides with the 42-foot elevation contour.

Geologically, the shoreline represents the most recent high-stand of prehistoric Lake Cahuilla. The lake gradually evaporated within the last several centuries. The lake is intimately tied to the fluctuations of the mouth of the Colorado River. The Salton Sea, which occupies a small portion of the Lake Cahuilla basin, is the result of an accidental diversion of the Colorado River in 1916. The deposits of Lake Cahuilla exposed in the park consist of a whitish, dry mud with ubiquitous shells and silty/sandy shoreline deposits. In geologic terms, the deposits are recent.

Archeologically, the shoreline represents the locus of prehistoric inhabitation by the Cahuilla Indians. Fish traps, trails, and other artifacts reveal how the Native Americans utilized the lake shore. The shoreline is approximately 280 miles long, but has been altered by development in many areas.

## Final Thoughts

There’s something brewing beneath this park. The multitudes of shallow earthquakes and high geothermal energy promise an interesting geologic future.

*Written by Mike Fuller, California Geological Survey*
*Photos: Cheryl Hayhurst (except where noted)*

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CALIFORNIA GEOLOGICAL SURVEY
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PLATE 1

## California's Bio-regions

### Klamath/North Coast Bioregion

#### Climate and Geography

Much of the Klamath/North Coast Bioregion is covered by forest—the Klamath, Shasta-Trinity, Six Rivers, and Mendocino National Forests, Jackson State Forest, and private forests, including the famous Headwaters ancient redwood forest in Humboldt County. This mountainous bioregion includes the North Coast Range and the Klamath, Siskiyou, Marble, Salmon, Trinity, and Cascade mountains. The Klamath/North Coast is the state's wettest climate, with rainfall distribution varying widely from an average annual 38 inches at Fort Bragg to 80 or more inches in the King Range National Conservation Area. The coastal climate is cool, moist, and often foggy, with rainy winters at lower elevations and snow in the higher mountains. Inland the climate is drier with low rainfall in winter and hot, dry summers.

Major rivers include the Eel, Trinity, Klamath, Russian, Smith, Salmon, Scott, Mad, and Mattole, which flows into the Pacific Ocean near seismically active Cape Mendocino. Clear Lake, Whiskeytown Lake, Clair Engle, and the western part of Shasta are the largest lakes in the bioregion.

#### Plants and Wildlife

Vegetation includes mixed conifer habitat of white fir, Douglas fir, ponderosa pine, Sierra lodgepole pine, incense cedar, sugar pine, red pine, Jeffrey pine, mountain hemlock, knobcone pine, western red cedar, red alder, redwood, tanoak, Pacific madrone, and chaparral.

Wetlands provide places for resting, nesting, feeding and breeding for native and migrating birds and waterfowl. Wildlife in the bioregion includes deer, fox, black bear, mountain lion, California clapper rail, Aleutian Canada geese, Roosevelt elk, osprey, fisher, bank swallow, Coho salmon, king salmon, otis blue butterfly, bald eagle, Point Arena mountain beaver, Swainson's hawk, willow flycatcher, western sandpiper, and Oregon silverspot butterfly.

Rare species include northern spotted owl, marbled murrelet, American peregrine falcon, Lotis blue butterfly, Trinity bristle snail, red-legged frog, Siskiyou Mountains salamander, Pacific fisher, Del Norte salamander, Karok Indian snail, wolverine, goshawk, and Chinook salmon. (Photograph by Christopher Mizeur.)

### Bay Area/Delta Bioregion

#### Climate and Geography

The temperatures in this Mediterranean climate don't vary much year-around. The coast experiences relatively cool, often foggy summers, mild falls, and chilly, rainy winters. Further inland, hot dry summers and warm autumns are followed by mild, wet winters. Snowfall is rare. The bioregion is mostly hilly with low coastal mountains and several peaks rising above 3,000 feet, including Mt. Diablo at 3,849 feet, in a state park. Coastal prairie provides grazing for wild and domestic animals, including dairy cattle.

The bioregion is named for its two major watersheds, San Francisco Bay and the Delta. Major rivers include the Russian, Gualala, Napa, Petaluma, and Alameda, and Putah Creeks. A network of reservoirs and canals comprise the State Water Project delivery system. Lake Berryessa in Napa County is the largest lake.

#### Plants and Wildlife

The habitats and vegetation of the Bay Area/Delta Bioregion are as varied as the geography. Coastal prairie scrub, mixed hardwoods and valley oaks are found among the rolling hills and mountains that descend to the ocean. Redwoods abound in Santa Cruz County. Coastal salt marsh lies around San Francisco Bay, and freshwater marshes are found in the Delta. Eucalyptus, manzanita, northern coastal scrub, California buttercups, goldfields, and Tiberon mariposa lily also are popular in the bioregion. Rare plants include Marin western flax, Baker's manzanita, Point Reyes checkerbloom, and Sonoma sunshine. Salt and freshwater marshes provide pickelweed, great bulrush, saltbush, and cattail.

Wetlands in the Bay-Delta—brackish and freshwater—furnish resting, nesting, feeding and breeding places for birds and waterfowl along the Pacific Flyway. These marshes, rich in biodiversity, are popular and necessary wintering spots for migrating birds.

Birds include canvasback, western grebe, black-crowned night heron, great egret, snowy egret, California brown pelican, white pelican, gull, acorn woodpecker, golden eagle, western bluebird, Caspian tern, American avocet, and cedar waxwing. Marine life includes Chinook salmon, harbor seal, sea lion, leopard shark, and bat ray. Other wildlife includes grey fox, mule deer, bobcat, raccoon, Pacific tree frog, and the swallowtail and painted lady butterfly.

Endangered species include the California least tern, California black rail and clapper rail, Smith's blue butterfly, salt marsh harvest mouse, California freshwater shrimp, northwestern pond turtle, and tidewater goby. (Photograph by Greg Kulak.)

### Central Coast

The Central Coast Bioregion features some of California's most beautiful coastal scenery, blessed with a mild, seasonally moist, and sometimes foggy climate that favors rich farmland and vineyards. This highly agricultural region is famous for artichokes, garlic, and an array of fruits and vegetables. Other industries include wine-making and dairy and cattle ranching. The coast supports a brisk fishing industry, and oil production along the southern end of the bioregion.

The bioregion extends some 300 miles from just north of Santa Cruz to just south of Santa Barbara, and inland to the floor of the San Joaquin Valley. It encompasses the counties of Santa Cruz, Monterey, San Benito, Santa Barbara, and portions of Los Angeles, San Luis Obispo, Fresno, Merced, Stanislaus, Ventura. The region includes such popular tourist attractions as the Monterey Bay area and Aquarium, Big Sur, the Hearst Castle, and the beaches of Santa Barbara, plus many state parks and other recreational attractions. The region also is the home of such well-known military installations as Fort Ord, Camp Roberts, and Vandenburg Air Force Base. The geography offers coastal mountain ranges including the Santa Lucia and Santa Ynez, and coastal sand dunes. vegetation includes chaparral, mixed hardwood and redwood forests in the bioregion's northern coastal area, and oak woodlands. the Los Padres National Forest covers much of the southern portion of the bioregion. The Salinas and Cuyama rivers feed the bioregion's two major watersheds. (Photograph by Jennifer Lotery.)

### South Coast

#### Climate and Geography

The year-around mild climate and varied geographical features of the South Coast contribute to its great popularity. Hot dry summers with predictable wildfires are followed by wet winters with storms that can trigger mudslides on fire-denuded slopes. Smog remains a serious problem in the South Coast bioregion, particularly the Los Angeles basin, but air quality regulations have helped to control it.

The South Coast bioregion is a study in contrasts—ocean and desert, flatlands and mountains, including 11,500-foot San Gorgonio Peak in Riverside County. Major rivers and their watersheds are: the Santa Clara, Los Angeles, Santa Ana, San Gabriel, San Luis Rey, San Jacinto, Santa Margarita, and San Diego. Publicly owned or managed lands include four national forests: the Angeles, Los Padres, Cleveland, and San Bernardino; numerous parks, state beaches, historic parks; and federal wilderness, recreation and wildlife areas, including Malibu Creek and Point Mugu State Parks, Bolsa Chica Ecological Reserve, Torrey Pines State Reserve, and Sweetwater and Tijuana National Wildlife Refuges. In San Diego, Orange and Riverside counties, the state's Natural Community Conservation Planning (NCCP) pilot program involving local, state, and federal partners is helping to protect the coastal sage scrub habitat of the threatened California gnatcatcher. In the Santa Monica Mountains, the National Park Service, Santa Monica Mountains Conservancy, and state Department of Parks and Recreation are helping to preserve spectacular habitat. In Ventura County, endangered California condors are protected at the Sespe Condor Sanctuary.

#### Plants and Wildlife

Tremendous urbanization in the South Coast bioregion has brought about the most intense effects on natural resources of any bioregion, resulting in alteration and destruction of habitat and proliferation of exotic or non-native species. In fact, the popular palm tree is not native to the Golden State. Habitat varies widely, from chaparral, juniper-pinyon woodland, and grasslands at lower elevations to mixed hardwood forest, southern oak, southern Jeffrey pine and southern yellow pine at higher levels. Along the coast, where real estate is especially prized, salt marshes and lagoons no longer are common habitat. But efforts are underway from Ventura County to the Mexican border to preserve and restore coastal wetlands.

The bioregion is home to mountain lions, coyotes, badgers, grey foxes, kit foxes, black bears, raccoons, mule deer, hawks, herons, golden eagles, ospreys, peregrine falcons, desert iguanas, dolphins, whales, endangered brown pelicans, and California sea lions. Rare animals include the Stephen's kangaroo rat, monarch butterfly, San Diego horned lizard, Peninsula desert bighorn sheep, orange-throated whiptail, California least tern, Belding's savannah sparrow, least Bell's vireo, Santa Ana sucker, arroyo southwestern toad and Tehachapi pocket mouse. (Photograph by MIke Fuller.)

### Colorado Desert

#### Climate and Geography

The Colorado Desert is the western extension of the Sonoran desert that covers southern Arizona and northwestern Mexico. It is a desert of much lower elevation than the Mojave Desert to the north, and much of the land lies below 1,000 feet elevation. Mountain peaks rarely exceed 3,000 feet. Common habitat includes sandy desert, scrub, palm oasis, and desert wash. Summers are hot and dry, and winters are cool and moist.

The Colorado River flows along the entire eastern boundary of the Colorado Desert bioregion on its way to Yuma, Ariz., where the two states and Mexico come together. The only other river of significant size in this bioregion is the polluted New River, which flows from Mexico into the Salton Sea, the region's largest body of water, on the border of Imperial and Riverside counties. The Salton Sea was created in 1905 when the Colorado River broke through an irrigation project and flooded a saline lake bed, creating an inland sea, which now lies about 235 feet below sea level and is some 35 miles long and 15 miles wide.

Anza Borrego Desert State Park, located mostly in eastern San Diego County, but jutting into Imperial County, is the bioregion's largest recreation area, covering 600,000 acres. It offers more than 225 bird species and dozens of mammals, amphibians, and reptiles. Bighorn sheep can be seen there, as well as thrashers and owls.

#### Plants and Wildlife

Other species in the Colorado Desert are Yuma antelope ground squirrels, white-winged doves, muskrats, southern mule deer, coyotes, bobcats, and raccoons. Rare animals include desert pupfish, flat-tailed horned lizard, prairie falcon, Andrew's dune scarab beetle, Coachella Valley fringe-toed lizard, Le Conte's thrasher, black-tailed gnatcatcher, and California leaf-nosed bat. (Photograph by Mike Fuller.)

### Mojave

#### Climate and Geography

The Mojave bioregion is the western extension of a vast desert that covers Southern Nevada, the southwestern tip of Utah, and 25 million acres of Southern California -- one quarter of the state. The climate is hot and dry in summer. Winters are cool to cold, depending on the elevation, with occasional rainstorms that can quickly turn a gulch or dry lake into a flash flood zone.

The landscape is mostly moderately high plateau with elevations averaging 2,000 to 3,000 feet and isolated peaks that exceed 6,000 and 7,000 feet. Though appearing barren and remote, the desert teems with biodiversity, and more than 90 percent is within three miles of a paved road or off-road vehicle track.

Palm oases provide water for wildlife, as do many streams and springs. In prehistoric times, the bioregion contained great desert lakes, which have long since evaporated and seeped underground. This bioregion has the lowest elevation in North America, 282 feet below sea level in Death Valley National Park. The Mojave, Amargosa, and Colorado Rivers are the largest rivers in this mostly arid bioregion.

#### Plants and Wildlife

Common habitats of the Mojave bioregion are: desert wash, Mojave creosote bush, scattered desert saltbush, Joshua tree scrub, alkali scrub, palm oasis, juniper-pinyon woodland, and some hardwood and conifer forests at higher elevations. Cottonwood willow riparian forest is rare habitat in this bioregion, as is alkali marsh and open sandy dunes.

Rare animals include the Mohave ground squirrel, prairie falcon, Le Conte's thrasher, Nelson's bighorn sheep, gray vireo, desert tortoise, pale big-eared bat, Amargosa vole, and Mohave tui chub, an olive-brown and silver fish, and the cottontail marsh pupfish, found only in Death Valley National Park. Parks and recreation areas that provide water are the home of snowy plovers, least sandpipers, killdeer, white pelicans, teal, and thousands of migratory wading shore birds, as well as eagles, harriers, falcons, owls, coyotes, badgers, great blue herons, least Bell's vireos, red-tailed hawks, and Canada geese. (Photograph by California Geological Survey staff.)

### Sierra Bioregion

#### Climate and Geography

The climate varies with the elevation, offering cold snowy winters and cool summers at higher elevations and rainy winters and mild summers in the foothills. Summers are dry. Snowy winters in the northern Sierra are crucial to California's water supply, which depends heavily upon spring snowmelt to feed the reservoirs of the State Water Project and a portion of the federal Central Valley Project. The projects supply about two-thirds of California's water for drinking, irrigation, and industrial use. Snowfall also is welcomed by the ski industry and a myriad of other businesses that serve and supply skiers. Mild dry mountain summers accommodate outdoor sports and activities, but when high pressure areas push temperatures upward and gusty winds blow, California is vulnerable to wildfires that consume thousands of acres of brush and timber every year.

National forests of the Sierra Bioregion are the Plumas, Tahoe, Sierra, Eldorado, Stanislaus, Sequoia, Inyo, and Toiyabe. Major rivers include the American, Feather, Yuba, Cosumnes, Tuolumne, Merced, San Joaquin, Kern, Owens, Kings, Carson, Truckee, Walker, and Stanislaus. Mono Lake east of Yosemite is famous for its peculiar tufa formations rising from the lake bed.

#### Plants and Wildlife

The Sierra Bioregion is rich in biodiversity, containing over half the plant species found in California and more than 400 of the state's terrestrial wildlife species, or about two-thirds of the birds and mammals and half the reptiles and amphibians. The variety of habitat types include annual grassland, blue oak savannah, chaparral, ponderosa pine, black oak woodland, mixed conifer, red fir, riparian, alpine meadow, Jeffrey pine, sagebrush, and bitter brush.

Animals that inhabit the Sierra Bioregion include lodgepole chipmunk, mountain beaver, California mountain king snake, black bear, wolverine, California big horn sheep, Pacific fisher, mule deer, and mountain lion. The California Golden Trout—the state fish—is native to the Southern Sierra. Birds include the northern goshawk, mountain chickadee, pine grosbeak, California spotted owl, mountain quail, willow flycatcher, bald eagle, and great grey owl. (Photograph by Chris Wills.)

Map of California Bio-regions

Reference: www.ceres.ca.gov/geo_area/bioregions

### San Joaquin Valley

#### Climate and Geography

Well-suited for farming, the bioregion is hot and dry in summer with long, sunny days. Winters are moist and often blanketed with heavy fog. The broad, flat valley is ringed by the Diablo and Coast Ranges on the west and the Sierra Nevada foothills on the east. Habitat includes vernal pools, valley sink scrub and saltbush, freshwater marsh, grasslands, arid plains, orchards, and oak savannah. The growth of agriculture in the Central Valley has converted much of the historic native grassland, woodland, and wetland to farmland.

The major river is the San Joaquin, with tributaries of the lower Stanislaus, Tuolumne, Merced, and Fresno rivers. The California Aqueduct extends the entire length of the bioregion. The southern portion of the bioregion includes the Kings, Kaweah, and Kern rivers, which drain into closed interior basins. No significant rivers or creeks drain into the valley from the Coast Range.

#### Plants and Wildlife

Historically, millions of acres of wetlands flourished in the bioregion, but stream diversions for irrigation dried all but about 5 percent. Precious remnants of this vanishing habitat are protected in the San Joaquin Valley bioregion in publicly owned parks, reserves, and wildlife areas. Seasonal wetlands are found at the Kern National Wildlife Refuge west of Delano, owned by the U.S. Fish and Wildlife Service. It attracts a variety of ducks, shorebirds, and song birds, as well as peregrine falcons.

The Tule Elk State Reserve west of Bakersfield, owned by the state Department of Parks and Recreation, features the habitat of the tule elk—natural grassland with ponds and marshes. The reserve sustains four endangered species—the San Joaquin kit fox, blunt-nosed leopard lizard, San Joaquin antelope squirrel, and Tipton kangaroo rat—the threatened plant Hoover's woolystar, and other rare species, such as western pond turtles, tricolored blackbird, and northern harrier. Endangered species of the bioregion also include the California tiger salamander, Swainson's hawk, and giant and Fresno kangaroo rat. Other rare species include the western yellow-billed cuckoo and valley elderberry longhorn beetle.

About one-fifth of the state's remaining cottonwood and willow riparian forests are found along the Kern River in the South Fork Wildlife Area. Great blue herons, beavers, coyotes, black bears, mountain lions, red-shouldered hawks, and mule deer can be seen in the wildlife area. Other wildlife viewing sites are Millerton Lake State Recreation Area west of Madera, Little Panoche Wildlife Area near Los Banos, and the Valley Grasslands of Merced County, which attract 500,000 to 1 million birds each winter to lands owned by the state Departments of Fish and Game and Parks and Recreation, Fish and Wildlife Service, and privately. The San Luis Dam and Reservoir area, jointly operated by the state Department of Water Resources and U.S. Bureau of Reclamation, draws wintering bald eagles, abundant ducks, gopher snakes, San Joaquin kit foxes, and black-tailed deer. (Photograph by Mike Fuller.)

### Sacramento Valley

#### Climate and Geography

The changing of the seasons is more evident in the Sacramento Valley than in the coastal regions to the west. Summer hot spells that drive daytime temperatures into triple digits are relieved by cooling "Delta breezes" that carry moist air from San Francisco Bay eastward through the Delta and into the Sacramento area, pushing the mercury back into the more comfortable 80s and 90s. Leaves turn gold during the brief, mild autumn that ends rather abruptly with the coming of winter fog around Thanksgiving. The so-called tule fog blankets the valley for much of the winter season from December into February, keeping temperatures chilled. Except during droughts, rainfall is frequent in winter, but snowfall is unusual because temperatures, particularly in the daytime, normally remain well above freezing.

The Sacramento Valley is flat for the most part, but is situated within distant view of mountains, which are particularly visible on clear days. To the west, the coastal range foothills loom on the horizon, while the snow-capped peaks of the Sierra Nevada can be seen to the east.

The valley's two major rivers—the Sacramento and American—carry water that originates in the Sierra Nevada south and west into the Sacramento-San Joaquin River Delta. The importance of the Delta cannot be overstated, for it supplies water to about two-thirds of California's 32 million population. Other rivers include the Cosumnes—the largest free-flowing river in the Central Valley—the lower Feather, Bear, and Yuba Rivers.

#### Plants and Wildlife

Oak woodlands, riparian forests, vernal pools, freshwater marshes, and grasslands provide the major natural vegetation of the Sacramento Valley Bioregion.

The Sacramento Valley is the most prominent wintering site for waterfowl, attracting more than 1.5 million ducks and 750,000 geese to its seasonal marshes along the Pacific Flyway. Species include northern pintails, snow geese, tundra swans, sandhill cranes, mallards, grebes, peregrine falcons, heron, egrets, and hawks.

Black-tailed deer, coyotes, river otters, muskrats, beavers, ospreys, bald eagles, salmon, steelhead, and swallowtail butterflies are just some of the wildlife that abounds in this bioregion. Species on the endangered species list include the winter-run Chinook salmon, delta smelt, giant garter snake, and the western yellow-billed cuckoo. (Photograph by Mike Fuller.)

### Modoc

#### Climate and Geography

The climate features hot dry summers and cold moist winters with snow at higher elevations. Geography is varied in the Modoc Bioregion,with volcanic areas and wetlands to the west and high desert to the east. Lassen Volcanic National Park, which is studded with lakes and crowned by 10,457-foot Lassen Peak; Tule Lake, and Clear Lake National Wildlife Refuges, Ahjumawi Lava Springs State Park, and Lava Beds National Monument are on the western side. The eastern side, which resembles its neighbor, Nevada, has desert alkali lakes, Honey Lake Valley, and Modoc National Wildlife Refuge. The last volcanic activity at Mount Lassen was in 1915.

As if to demonstrate the variation of the bioregion's landscapes, the 25-mile Bizz Johnson Trail linking Susanville and Westwood follows a railroad grade from high desert through grasslands and oak woodlands into a dense forest of pine and cedar.

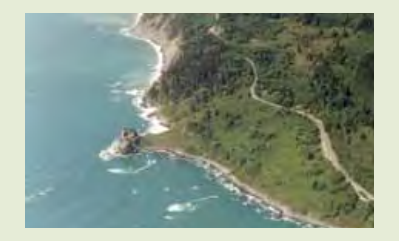
The bioregion includes Modoc and Lassen National Forests and part of the Klamath National Forest. The largest lakes are Lake Almanor in Plumas County, Eagle Lake in Lassen County, Lower Klamath Lake in Siskiyou County, and Goose Lake in Modoc County. The Pit River flows southwest from the rugged Warner Mountains in eastern Modoc and Lassen counties across the Modoc Plateau and into the Sacramento River.

#### Plants and Wildlife

Juniper and sagebrush cover much of the eastern side of the Modoc Bioregion, while yellow and Jeffrey pine, white fir, mixed conifer, cedar, and aspen are common in the more mountainous and forested areas to the west. Wildlife include bald eagles, antelope, greater sandhill cranes, ospreys, Canada geese, black-crowned night herons, mule deer, muskrats, pronghorn, cinnamon teal, northern pintails, Swainson's hawks, sage grouse, rainbow trout, marmots, hummingbirds, great horned owls, black bears, coyotes, porcupine, Modoc sucker, goshawk, bank swallow, Shasta crayfish, sage grouse, and Lost River sucker. (Photograph by Michael Wopat.)

# Geologic Gems of California's State Parks

California is a veritable treasure chest of nationally acclaimed natural landmarks and much adored scenery. This geologic legacy on display in the landscape can be observed throughout California's State Park system. We selected exemplary units of the State Park system to highlight California's geologic legacy. The selected parks are dubbed "GeoGems."



The rugged cliffs of **Del Norte Coast Redwoods State Park** are composed of some of the most tortured, twisted, and mobile rocks of the North American continent. The rocks are mostly buried beneath soils and covered by vigorous redwood forests, which thrive in a climate famous for summer fog and powerful winter storms. The rocks only reveal themselves in steep stream banks, along road and trail cut banks, along the precipitous coastal cliffs and offshore in the form of towering rock monuments or sea stacks. (Photograph by CalTrans staff.)

**Patrick's Point State Park** displays a snapshot of geologic processes that have shaped the face of western North America, and that continue today. The rocks exposed in the seacliffs and offshore represent dynamic interplay between the subducting oceanic tectonic plate (Gorda Plate) and the continental North American tectonic plate. The boundary between the subducting oceanic plate and the continent has been filled with an "accretionary wedge" of material literally scraped off the oceanic floor and crust, partially subducted, and then pasted to the North American continent. (Photograph by Jim Falls.)

**Humboldt Redwoods State Park** has international reknown and is classified as both a World Heritage Site and an International Biosphere Reserve. The coast redwoods (sequoia sempervirens) exist only in a narrow band that runs for 500 miles from Monterey to just over the Oregon border. Needing a warm, moist, and foggy environment, coast redwoods are confined to the coast and elevations below 3,000 feet. Redwoods are "living fossils" dating back 100 million years to the Cretaceous Period—the time of the dinosaurs. The oldest redwoods range from several hundred to as much as 2,000 years old. Old growth groves are truly monuments of the past. Prior to the Ice Ages (1.8 million years ago), the redwood forests were much more widespread but became restricted to their present range due to cooler temperatures and regional uplift of the Coast Ranges. (Photograph by Bret Koehler.)

**Sinkyone Wilderness State Park** occupies a very distinguished geologic location near the junction of three of the major plates that make up the earth's crust. These three tectonic plates (the Pacific, North American, and Gorda plates) are bounded by major faults, including the San Andreas Fault just offshore of the park and the Mendocino fracture zone and Cascadia "mega-thrust" (a subduction zone) offshore and north of the park. (Photograph by Don Braun.)

The Ten Mile Dunes complex at **MacKerricher State Park** contains a unique, relatively pristine native dune and wetland ecosystem. The effects of climate change over the past several thousand years have been recorded by sediment deposits along the coast. Recurrent periods of dune formation and sea level oscillation have been associated with the Ice Ages and more recent climatic events. These shifting sands of time produced enclosed areas of water ponding that became vegetative microclimates such as Inglenook Fen and Sandhill Lake. (Photograph Copyright 2002–2009 by Kenneth and Gabrielle Adelman.)

At **Jughandle State Natural Reserve,** some lands are preserved not only for their scenic beauty or wilderness qualities, but are also protected because they are ecologically unique, such as the pygmy forest. The sequence of terraces provides a 500,000-year-long timeline of soil and plant community development that shows the interplay of biology and geology like nowhere else. (Photograph Copyright 2002–2009 by Kenneth and Gabrielle Adelman.)

Geologic oddities at **Schooner Gulch State Beach** have arisen from unusual combinations of unrelated geologic conditions. One such example is Bowling Ball Beach where concretions (odd enough in their own right), tilted outcrops of alternating hard and soft strata (not unusual), and wave erosion along the coastline (very common) combine to create a very unusual spectacle. Fortunately, the State of California values these treasures and protects them for all to see in their natural setting. (Photograph by Jennifer Lotery.)

At **Salt Point State Park**, how and why tafoni has formed remains a geological mystery. The beds that formed from density currents reveal undersea processes and conditions that are rarely witnessed. These exposures are a magnet for study by amateurs, students, and professional geologists. The beds lie immediately west of the San Andreas Fault and provide a key timeline and geologic marker for fault studies. (Photograph by Mike Fuller.)

At **Robert Louis Stevenson State Park**, unlike most of the northern California Coast Ranges, the Mayacama Mountains are largely volcanic in origin. The rocks that form Mount St. Helena and the Palisades are part of a group of rocks known as the Sonoma volcanics. The Sonoma Volcanics erupted from a number of different volcanic centers in the Napa-Sonoma region between 2.6 and 8 million years ago. (Photograph by Mike Fuller.)

The landforms and underlying geology found at **Fort Ross State Historic Park** illustrate a dynamic history of shifting tectonic plates (giant fragments of the earth's crust) and fluctuating sea level. The park is situated at the active continental margin, where the Pacific Plate and the North American Plate are moving slowly past each other along the San Andreas Fault. East of the fault, rocks of the Franciscan Complex form the core of the northern California Coast Ranges. To the west, rocks of the Point Arena terrane represent a displaced sliver of the earth's crust that has been dragged northward along the fault for millions of years. (Photograph by Mike Fuller.)

At **Mt. Tamalpais State Park**, the Franciscan Complex has perplexed geologists from around the world, and has served as an important proving ground for modern plate tectonic theories. It provides an excellent above-ground laboratory of what happens in subduction zones beneath the oceanic crust and continental crust. (Photograph by Mike Fuller.)

**Mount Diablo** is a dominant topographic feature in northern California. It was established in 1851 as the initial point of the Mount Diablo Base Line and Meridian for land surveys spanning two-thirds of California and all of Nevada. The mountain's summit boasts spectacular panoramic views. (Photograph by Mike Fuller.)

**Wilder Ranch State Park** is situated in the California Coast Ranges at the continental margin, a tectonically active zone where the San Andreas Fault system forms the boundary between the Pacific Plate and North American Plate. As these two enormous pieces of the earth's crust grind slowly past one another, the lands along the plate boundary have been sheared, buckled, squeezed and deformed on a monstrous scale. (Photograph by Mike Fuller.)

The landforms and underlying geology found at **Hollister Hills State Vehicular Recreation Area** embody a dynamic history of shifting tectonic plates—giant fragments of the earth's crust. The park is situated at the active continental margin, where the Pacific Plate and the North American Plate are moving slowly past each other along the San Andreas Fault. (Photograph by Steve Reynolds.)

At **Point Lobos State Natural Reserve**, the rocks offer many interesting features for inquisitive visitors to contemplate, but are of particular significance to geologists because they provide clues to decipher movements along the San Andreas Fault system and to the dynamic history that produced the California Coast Ranges. (Photograph by Mike Fuller.)

**Morro Bay State Park** and **Montaña de Oro State Park** are renowned for their spectacular scenery produced over millions of years by volcanic activity, plate tectonic interactions (subduction and collision), and erosion to shape this unique landscape. Marine terraces are evidence of regional uplift. (Photograph by Alan Schimierer.)

The rocks that make up **Point Sal State Beach** represent one of the most intact and complete cross sections of oceanic crust visible on land. Oceanic crust comprises 60% of the earth's crust, yet we rarely have opportunities to see it and study its formation. The rocks at the park record geologic conditions that indicate submarine origin and widespread transport via plate tectonics. Oceanic crust is produced at ocean spreading centers and consumed in subduction zones. (Photograph by Will Harris.)

**Hungry Valley State Vehicular Recreation Area** lies in the heart of a complex geologic structure known as the Ridge Basin. The highly deformed rocks within the park bear stark witness to the tremendous forces that characterize the interplay between the San Andreas and San Gabriel Faults, which bound the basin and the park. (Photograph by Steve Reynolds.)

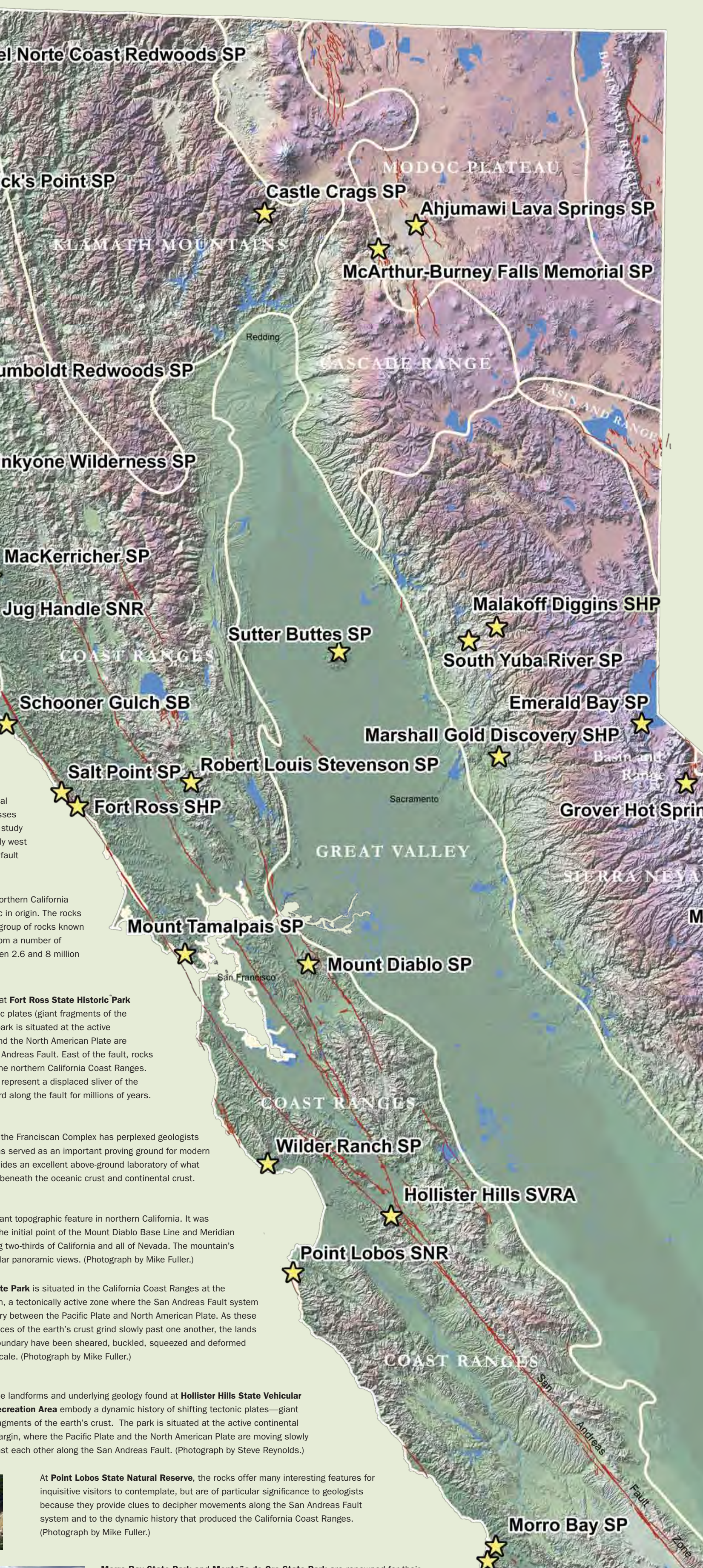
The coastal bluffs at **Gaviota State Park** reveal a 500-foot-thick cross-section of the geographically extensive Monterey Formation. Offshore and inland, petroleum geologists have extensively explored underground for oil reservoirs within this rock sequence and probed its depths to understand the genesis of this important oil source. The naturally cemented, bluff faces resist wave erosion and are tilted to display multiple layers like the pages of a book. The geologic layers contain some nicely preserved fossils, even the complete skeleton of a halibut-like fish. (Photograph by Mike Fuller.)

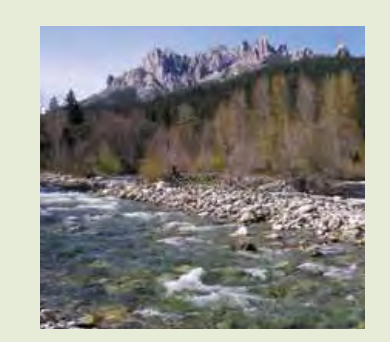
**Malibu Creek State Park** contains excellent exposures of the Conejo Volcanics that cover large portions of the modern Santa Monica Mountains of the Transverse Ranges geomorphic province. The Conejo Volcanics are one of several Miocene volcanic fields along the California coast that erupted in response to a major reorientation of the tectonic plate boundary between the North American tectonic plate, the subducting Monterey microplate, and the better-known Farallon Plate. The reorientation caused local areas of extension and crustal thinning. The molten rocks below the thin oceanic crust ascended through the crust along fractures to the surface and erupted as volcanic rocks. (Photograph by Pam Irvine.)

**San Onofre State Beach** exemplifies the joys and challenges of living on the fragile coast. The scenic beauty derives from the panoply of geologic processes, many of which can be hazardous and difficult to manage. Landslides, massive erosion, and earthquakes are the results of a long geologic history that is readily on display within the park. (Photograph by Mike Fuller.)

**Anza-Borrego Desert State Park's** rugged landscape formed largely by the forces of erosion attacking the uplifted mountains. The higher the mountains rise, the more vigorously they are attacked by rain, snow, ice, and wind, as they yield to the constant pull of gravity. (Photograph by Mike Fuller.)

**Torrey Pines State Natural Reserve** preserves habitat for North America's rarest and most geographically restricted type of pine tree species. Several natural processes interact to form the habitat for the pines. The reserve and beach are perfect places for visitors to see vestiges of past environments and their continuing influence on the landscape and to envision the dynamics of shoreline processes. (Photo by Mike Fuller.)





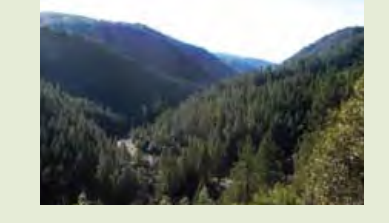
Few of California's State parks display impressive monoliths adorned like a castle with towering spires and few permit rock climbing. **Castle Crags State Park** is an exception. The scenic beauty is best enjoyed from a distant vantage point where one can see the range of surrounding landforms. The monolith and its surroundings are a microcosm of the Klamath Mountains where many such monoliths intrude and stitch together a crazy quilt of much older rocks. The surrounding rocks include the Trinity ultramafic sheet, the largest exposed body of ultramafic rock in North America. The ultramafic rock is often interpreted to represent an ancient ophiolite—a slice of the oceanic crust. (Photograph by Christopher Mizeur.)

"Ahjumawi" means "where the waters come together" in the Ajumawi language. This is a particularly appropriate description for **Ahjumawi Lava Springs State Park**, since the waters of Big Lake, Tule River, Ja She Creek, and Fall River all come together at this location. The springs at the park comprise one of the largest fresh water spring systems in the country. They discharge into Big Lake, Horr Pond, and Ja She Creek, which together form the headwaters of the East Fork of the Tule River (a major tributary to the Fall River). (Photograph by Michael Wopat.)

Burney Falls at **McArthur-Burney Falls Memorial State Park** is an outstanding example of a waterfall and stream fed by large springs that are commonly associated with areas covered by recent lava flows, and also of a waterfall formed by the undercutting of horizontal rock layers. The soft white rock is diatomite. Its presence is evidence that a very large lake once filled the region and supported abundant tiny freshwater plankton called diatoms. (Photograph by Michael Wopat.)

**Sutter Buttes State Park** contains the remains of a period of violently active volcanic eruptions between 1.35 and 1.6 million years ago. The origin of the Sutter Buttes has been hotly debated. The volcanic activity has been variously related to the Cascade Range to the North, to the Sonoma volcanics to the south and west, and to plate tectonic interactions deep below the terrestrial crust. (Photography by Mike Fuller.)

At **Malakoff Diggins State Historic Park**, the ancient river gravels are important from a geologic perspective in that they provide insight into the timing of the geologic events that gave rise to the current Sierra Nevada. From the human perspective, the gold in the gravels was a source of vast wealth that drove the development of early California. (Photograph by Mike Fuller.)



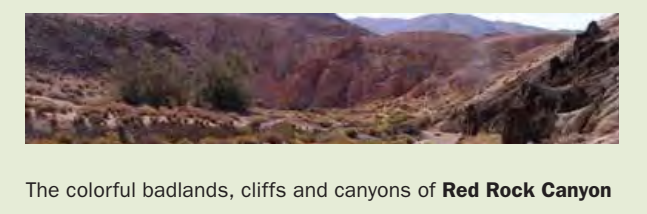
Once the **South Yuba River** watershed was the focal point of the California Gold Rush. Today, it is recognized by the California State legislature as a Wild and Scenic River with scenery of "Outstandingly Remarkable Value." This park which follows the river for twenty miles provides a very scenic geologic cross-section of a part of the State that played such prominent roles both geologically and economically in California's history. (Photograph by Mike Fuller.)

**Emerald Bay State Park** is the California State Park system's premier glacial park—owing its spectacular scenery and dramatic alpine peaks, ridges, and crystalline lake to the scouring action of glaciers that existed at various times during the Pleistocene Epoch (11,500 to 1,800,000 years ago). Glaciers as thick as several hundred feet buried all but the highest peaks of the Sierra and tongues of ice pushed down from the Sierran crest and gouged out stream canyons, scraped off soil and weathered rock, deposited moraines and carved out lake basins. (Photograph by Mike Fuller.)

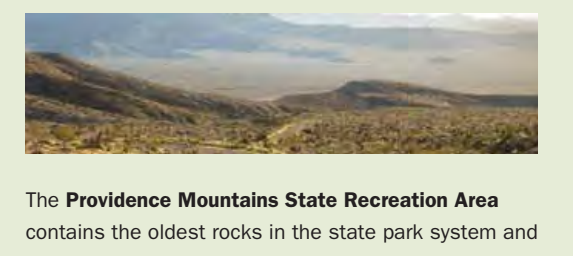
**Marshall Gold Discovery State Historic Park:** Although small amounts of gold had been found in other parts of California, it was the gold discovery at Sutter's mill that received world-wide attention in 1848. The discovery caused one of the largest mass-migrations in history, bringing people to California from all over the world. Most prospectors who came did not strike it rich in the gold fields and returned home, but about ten percent stayed in California. Those who stayed contributed to California's unprecedented rapid commercial, agricultural and industrial development and statehood in 1850. (Photograph by Mike Fuller.)

**Grover Hot Springs State Park** is treasured for its beautiful alpine setting and alleged restorative and refreshing natural hot springs. For more than 100 years nature lovers have been drawn to the springs to bask in the warm mineral waters and absorb the pleasant views of the tranquil peaks surrounding the hot springs meadow. (Photograph by Mike Fuller.)

**Mono Lake Tufa State Natural Reserve** is one of the rare places in the world that contain such a unique group of geologic features. The tufa formations are notable for their unusual shapes and abundance. Extensively studied by scientists, they have aided our understanding of the climate history of this region. The extremely high salinity and alkalinity of Mono Lake has created a rare ecosystem, supporting a complex food chain of green algae, brine shrimp and alkali flies, and more than 80 species of migratory birds. (Photograph by Milke Fuller.)

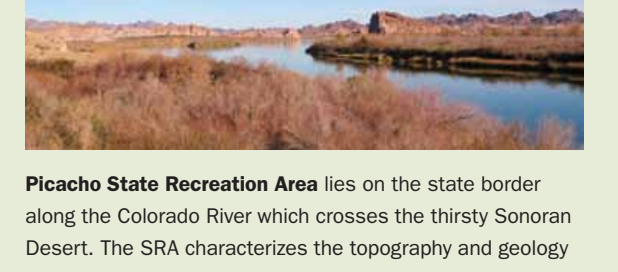


The colorful badlands, cliffs and canyons of **Red Rock Canyon State Park** provide more than pretty scenery and a backdrop for movies. Hidden behind the scenes in the layers of rock is what amounts to paleontologists as a treasure trove. For almost a century, paleontologists have been combing through these layers and making important discoveries about the history of mammalian life in these parts. (Photograph by Will Harris.)

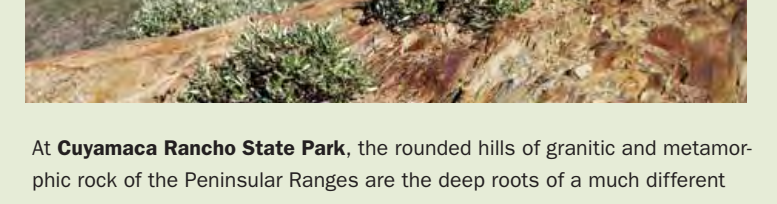


The **Providence Mountains State Recreation Area** contains the oldest rocks in the state park system and some of the most spectacular limestone caves in all of California. The caves are important to visitors for their spectacular beauty, but they also provide abundant information about the geologic and climatic history of the region. (Photograph by California State Parks.)

Major geologic forces are at play at **Ocotillo Wells State Vehicular Recreation Area** which is caught in a tug-of-war along the boundary between the North American and Pacific Plates. As the Peninsular Ranges of southern California and Baja move to the northwest with the Pacific Plate, they pull apart and tear the plate boundary along the San Jacinto Fault and the Salton Trough. (Photograph by Mike Fuller.)



**Picacho State Recreation Area** lies on the state border along the Colorado River which crosses the thirsty Sonoran Desert. The SRA characterizes the topography and geology of eastern California's Mojave Desert Geomorphic Province which overlaps the Sonoran Desert. This geologic landscape is continuous throughout southern Arizona—home of the northern Sonoran Desert. (Photograph by Mike Fuller.)



At **Cuyamaca Rancho State Park**, the rounded hills of granitic and metamorphic rock of the Peninsular Ranges are the deep roots of a much different ancient range that included volcanoes and high mountains possibly like the Andes. By examining these roots, we learn about the internal workings of other mountains. (Photograph by Janis Hernandez.)

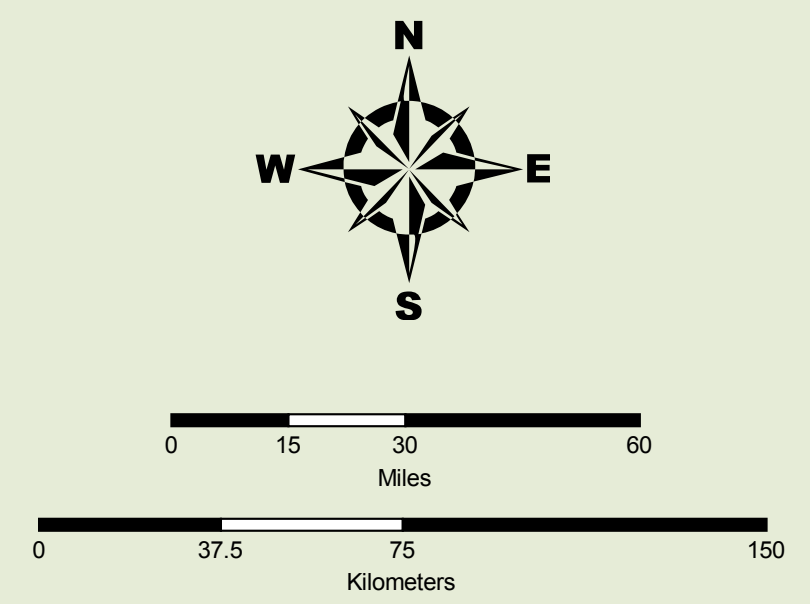
★ State Park GeoGems

SP: State Park
SB: State Beach
SHP: State Historic Park
SRA: State Recreation Area
SNR: State Natural Reserve
SVRA: State Vehicular Recreation Area

▭ Geomorphic Provinces

▬ Holocene Faults Active Within Last 11,000 Years

GIS Development and Map Layout by Mike Fuller, C.E.G.,and Jim Thompson



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## California's Geomorphic Provinces

The **Klamath Mountains** consist of several rugged ranges and deep canyons. The mountains reach elevations of 6,000 to 8,000 feet. In the western part of the province, the irregular path of the Klamath River is incised into an uplifted plateau often referred to as the Klamath peneplain. The uplift has left successive benches with gold-bearing gravels on the sides of the canyons. The province is considered to be a northern extension of the Sierra Nevada. Rocks include metamorphosed Paleozoic and Mesozoic oceanic rocks, abundant serpentinite, and granitic intrusions.

#### Tectonic Setting

The oceanic rocks and serpentinite represent accreted terranes with the latter being interpreted as an ophiolite. Several distinct terranes have been identified. The terranes have been intruded by granitic plutons and veins. Veins, which crosscut adjacent terranes, formed after accretion and help constrain the history. Studies that dated rocks in the province show the terranes are progressively younger from east to west, ranging from Devonian to Late Jurassic Periods (416 to 190 million years ago.) (Photograph by Christopher Mizeur.)

The **Coast Ranges** are a series of relatively low mountain ranges and associated valleys that trend northwest, subparallel to the active San Andreas Fault. Elevations of the ranges are typically 2,000 to 4,000 feet, sometimes reaching 6,000 feet above sea level. The Coast Ranges are predominantly composed of thick late Mesozoic and Cenozoic (251 million years ago to present) sedimentary rocks. The northern and southern portions of the province are separated by a depression containing the San Francisco Bay.

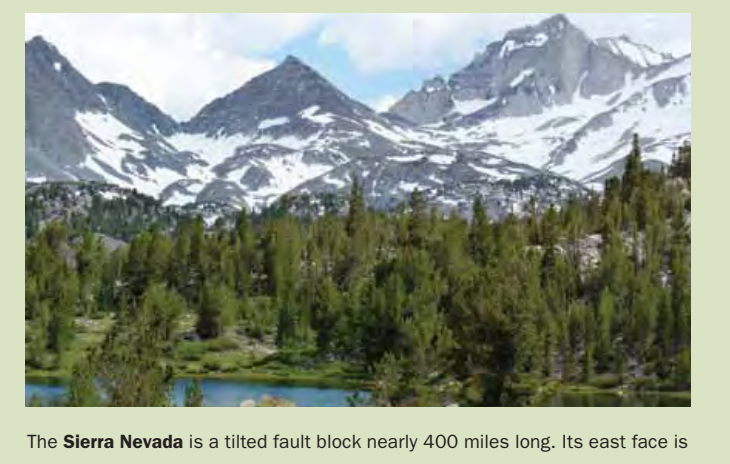
In some areas of the Coast Ranges, the topography is dominated by irregular, knobby outcrops of the landslide-prone rocks of the Franciscan Complex. In the Sonoma and Clear Lake regions Pliocene and younger volcanic flows, ash deposits, and cones are prominent. In the southern Coast Ranges, granitic and metamorphic rocks of the Salinian block lie to the west of the San Andreas Fault and extend from the southern extremity of the Coast Ranges, north to the Farallon Islands.

#### Tectonic Setting

The Coast Ranges record both an ancient period of subduction and a subsequent regime of sideways deformation that persists today.

The rocks of the Coast Ranges (referred to as the Franciscan Complex) formed as a massive pile of rock and sediment in an ancient subduction zone. The bulk of the formation is a sheared matrix with large blocks of various rock types (mélange). Adjacent enclosed blocks exhibit distinctively different metamorphic histories. Pieces of the former subducting oceanic plate, known as the Coast Range ophiolite, are scattered throughout the province.

The San Andreas Fault system, consisting of numerous splays, runs almost the entire length of the Coast Ranges. To some degree, the San Andreas Fault system has shaped the landscape across the whole province south of the Mendocino triple junction. The movement along the faults for the past 20 million years has been generally strike-slip. The landscape reflects this sideways deformation with local areas of uplift or subsidence often reflected as parallel sequences of linear valleys and ridges. (Photograph by Mike Fuller.)



The **Sierra Nevada** is a tilted fault block nearly 400 miles long. Its east face is a high, rugged fault scarp that contrasts sharply with its gentle western slope. The massive granites of the higher elevations are modified by glacial sculpting, forming such scenic features as Yosemite Valley. Many west-flowing rivers cut deeply into the western slope. The high crest of the range culminates in Mt. Whitney with an elevation of 14,495 feet above sea level. The older metamorphic bedrock, in places still partly capped by much younger Tertiary volcanic rocks, contains gold-bearing veins associated with the northwest-trending Mother Lode.

#### Tectonic Setting

The Sierra Nevada foothills, source of California's famous gold deposits, consist of ancient accreted terranes and one or more former subduction zones. The subduction zone(s) operated during the Mesozoic Era, 140 to 180 million years ago. The former Farallon oceanic tectonic plate was driven beneath the present day Sierra where it melted into large molten bodies known as batholiths and plutons. The terranes and sediments that accumulated in the subduction zone of this former plate boundary have been metamorphosed by the heat and fluids that radiated off the molten batholiths and plutons that eventually cooled to become the Sierran granitic rocks.

Over the last five million years, faults developed along the eastern margin of the Sierra Nevada along which the range has risen to tower above the Basin and Range province to the east. Active faults and hot springs (characteristic of the Basin and Range) penetrate the Sierran monolith and demonstrate that the boundary zone is still evolving.

The uplift of the Sierra Nevada changed the climate in California and Nevada. The mountains became a barrier to storms originating in the Pacific Ocean that moved eastward over the land. In effect, California became wetter at the expense of Nevada. This increased precipitation allowed glaciers to cover the high Sierra during the Ice Ages of the past 100,000 years. The high Sierra parks (Emerald Bay State Park and Grover Hot Springs State Park) owe some of their majestic beauty to the effects of long gone glaciers. (Photograph by Mike Fuller.)

The **Colorado Desert** geomorphic province, between the Mojave Desert and the Peninsular Ranges geomorphic provinces, occupies a major boundary zone, the plate boundary. The province is mostly below sea level and is the on-land extension of the Gulf of California. The low-lying arid basin is occupied by the Salton Sea (surface elevation about 245 feet below sea level). Surrounding the Salton Sea are the ancient beach lines and silt deposits of extinct Lake Cahuilla. As a testament to the near-surface tectonic activity, there are several developed geothermal areas in the southern section.

The province hasn't always been so dry. The Colorado River that runs from Colorado and through the Grand Canyon has long delivered its heavy sediment load to the Gulf of California. The precise areas of sediment deposition shifted back and forth over time. Eventually the river delta became large enough to plug the Gulf and exclude the seawater from California. The seawater trapped in this province evaporated. On several occasions the lower Colorado River shifted course and sent water and sediment north of the plug instead of south. This resulted in a series of large freshwater lakes that eventually evaporated.

#### Tectonic Setting

The mid-oceanic ridge runs the length of the Gulf of California and is a major rift zone between oceanic plates. Based on seismic activity, the rift appears to be advancing northward into the Colorado Desert geomorphic province. The San Andreas Fault system joins into the growing rift in very complex and confounding ways. This is one of the most seismically active places in California. The crust is so thin that geothermal energy is abundant in this very hot, parched place. (Photograph by Cheryl Hayhurst.)

The **Peninsular Ranges** geomorphic province consists of a series of mountain ranges separated by long valleys, formed from faults branching from the San Andreas Fault. The topographic trend is similar to the Coast Ranges, but the geology is more like the Sierra Nevada, with granitic rocks intruding the older metamorphic rocks. The Los Angeles Basin and the Channel Islands of Santa Catalina, Santa Barbara, San Clemente and San Nicolas are included in this province. Also included is the surrounding continental shelf (cut by deep submarine fault troughs). At the northern end of the province Mount San Jacinto forms the dramatic backdrop to the Coachella Valley more than 10,000 feet below. The Peninsular Ranges extend south across the international border into Baja California, forming the spine of Baja California.

#### Tectonic Setting

The Peninsular Ranges and the very similar Sierra Nevada probably formed in similar tectonic environments during the same period of time. However, they currently lie on opposite sides of the tectonic plate boundary represented by the San Andreas Fault system. The Peninsular Ranges are slowly moving northward along the coast headed toward Alaska. (Photograph by Mike Fuller.)

The **Cascade Range**, a chain of volcanic cones, extends from southern British Columbia through Washington and Oregon into northern California. Cascade volcanoes are large cone-shaped mountains built by very explosive eruptions that produced extreme volumes of ash deposits. In California, Mount Shasta, a glacier mantled volcanic cone, rises 14,162 feet above sea level and is one of the world's largest composite volcanoes. At the southern end of the Cascade Range is Lassen Peak, a very large plug dome, which last erupted during the period of 1914 to 1921. Between these two volcanic centers, the Cascade Range is transected by the deep canyon of the Pit River, which eventually joins with the Sacramento River. Prehistoric eruptions within this mountain range left several enormous calderas, such as Crater Lake and the area partially occupied by Mount Lassen.

Just 30 miles east of Mount Shasta lies Medicine Lake volcano, a large shield volcano—so named for its broad and rounded, low profile. Despite its low profile, it is believed to be the largest of the Cascade volcanoes. Medicine Lake occupies a large caldera. Its different shape relates to the less viscous (more fluid) magma that feeds it.

#### Tectonic Setting

The Cascade volcanic rocks result from the subduction and partial melting of the Gorda tectonic plate in the active Cascadia subduction zone. The Mendocino triple junction marks the southern limit of the subduction zone. Many of the Cascade volcanoes are either active or potentially active.

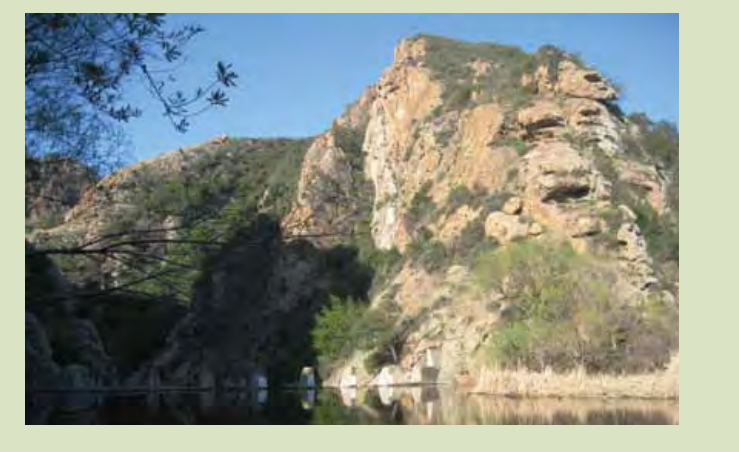
At Medicine Lake, the magma and style of volcanism is more characteristic in regions undergoing crustal thinning and extension such as in the Modoc Plateau and the Basin and Range provinces. But it also shows characteristics of the Cascades. This is an excellent example of overlap in geomorphic boundary zones. (Photograph by Shannon Utley.)

The **Coastline** (not illustrated in main map) qualifies as a distinct geomorphic subprovince evenly divided between north and south. Because the coastline is 1,100 miles long, the climate and water temperatures in the south are more mild than in the north. The flora and fauna vary accordingly. The California coastline is a dynamic boundary zone, of varying width, where geologic forces collide. Coastal landforms include beaches, dunes, tide pools, estuaries, lagoons, steep cliffs, marine terraces, and sea stacks.

The coastline can be subdivided into two sections. The northern section runs the length of the Coast Ranges province; the southern runs along the western edge of the provinces of the Transverse Ranges and the Peninsular Ranges. Along the northern section, the coastal geomorphology is superimposed on the landforms of the Coast Ranges province. Along the southern section, the coastal geomorphology is superimposed on the landforms of the Transverse Ranges and Peninsular Ranges geomorphic provinces. The northern section runs north-by-northwest from Point Conception north to Oregon. Due to the orientation, the winter storms and waves tend to attack the northern shores head-on without the buffering effect of a broad continental shelf. Beaches are often cobbly or gravelly with scattered sandy beaches.

The southern coastline trends northwestwardly from San Diego to Point Conception. Due to the orientation, the southern shores are somewhat sheltered from storms that arrive from the west and northwest. A broad continental shelf lies along the southern section. The shallow offshore shelf helps absorb wave energy by causing waves to break further from shore. Sand deposition in the form of beaches started roughly 10,000 years ago and is relatively widespread along the southern coast.

The position of the shoreline is directly related to sea level and land elevation both of which are variable through time. Sea level was as much as 400 feet lower during the last Ice Age because so much water was trapped as ice on the glaciers that covered northern and southern latitudes. During this time the shoreline position was as much as several miles west (near the Farallon Islands) of its current location. During the Ice Ages, major rivers cut deep canyons into the continental shelf creating submarine canyons such as the Monterey submarine canyon, which is twice as deep as the Grand Canyon. During the last interglacial, sea level was approximately 15-20 feet higher and coastal wetlands and estuaries were correspondingly much more extensive than today. (Photograph by Jennifer Lotery.)



The **Transverse Ranges** are a complex series of east-west trending mountain ranges and valleys that strongly contrast with the northwest trend of the adjacent Coast Ranges and Peninsular Ranges. The section of Cenozoic sedimentary rocks within this province is one of the thickest in the world and regional structural trends are significant in the formation of important oil field structures.

The western limit of the province contains the islands of San Miguel, Santa Rosa, and Santa Cruz. The eastern limit, extends into the Mojave Desert, and includes the San Bernardino Mountains to the east of the San Andreas Fault. Within the Transverse Ranges, the San Bernardino and San Gabriel Mountains contain some of the highest peaks in southern California, ranging from 10,000 to over 11,500 feet above sea level.

#### Tectonic Setting

The Transverse Ranges are caught in a geological vise that has been squeezing them for the past 20 million years, from south to north producing high amplitude compressed folds and faults. The troughs of the folds became deep marine basins and the peaks are expressed as the ranges. The exceptionally thick sediments were at first rapidly deposited into the deep marine basins; then with continued compression were pressed up into the ranges. Tectonic models suggest that the Ranges rotated nearly 100 degrees clockwise due to plate tectonic movements.

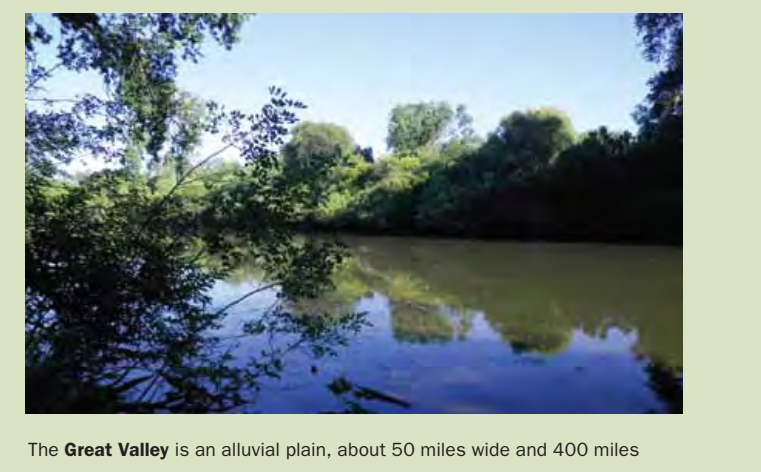
The Transverse Ranges are bisected by the San Andreas Fault system representing a complex section of the tectonic plate boundary. This compression is thought to result from what is called the "Big Bend" in the San Andreas Fault. Overall, the trend of the San Andreas is north by northwest but in this section it bends counterclockwise, that is more northwest. In simple terms, the lands northeast of the boundary are riding on the North American plate with its northwest heading. The lands southwest of the boundary are riding on the more northerly drifting Pacific plate which is pushing into the North American plate. (Photograph by Pam Irvine.)

Map of California Geomorphic Provinces

The **Modoc Plateau** is a volcanic tableland with elevations ranging between 4,000 and 6,000 feet above sea level. Most of the volcanic rocks erupted as extensive fluid lava flows during the Tertiary period, between 10 and 2 million years ago. The Modoc plateau eruptive centers consists of fissures and many small cones. Eruptions were nowhere near as explosive as the Cascade volcanoes. Instead, the volcanic products consist of a thick accumulation of lava flows and tuff/ash beds that have built the plateau. Many northerly-trending faults cut across the plateau, breaking it up into tilt-block mountains.

#### Tectonic Setting

This style of volcanism occurs in regions experiencing crustal thinning and extension such as in the Basin and Range geomorphic province to the east. The region consists of 1) Tertiary and Pleistocene basalt lava flows with more recent flows at the edge of the Cascade Range geomorphic province and 2) closely spaced, northerly-trending faults characteristic of the Basin and Range province. The Modoc Plateau geomorphic province can be thought of as a broad boundary zone between the Cascade and Basin and Range provinces. (Photograph by Michael Wopat.)

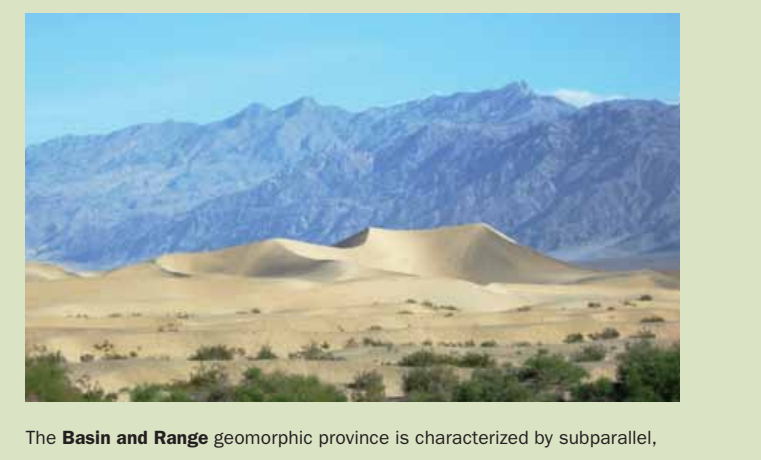


The **Great Valley** is an alluvial plain, about 50 miles wide and 400 miles long, located between the Coast Ranges and the Sierra Nevada. It is drained by the Sacramento and San Joaquin Rivers, which join and enter San Francisco Bay. To the north, the Sacramento Valley floodplain is interrupted by the Sutter (Marysville) Buttes, an isolated Plio-Pleistocene volcanic plug about 2,000 feet high. The valley is filled with nearly flat-lying sediments as much as 20,000 to 40,000 feet thick. Beneath the valley, Cretaceous and Cenozoic strata form a broad U-shaped cross-sectional profile (trough) that is steeper on the west than the east. The edges of the tilted layers of Great Valley sedimentary rock can be seen along the western margin of the trough adjacent to the Coast Ranges. In the southern part of the Great Valley, the San Joaquin Valley oil fields follow uplifts and fault warps that formed "traps" for petroleum, such as those found in the Kettleman Hills.

The Great Valley has become one of the leading agricultural regions in the world due to a mild climate and extensive, fertile soils. These soils formed in wetlands as floodplain deposits replenished by sediment carried in the Sierran rivers during periodic, large floods. The floods and vast wetlands delayed the development of the Great Valley. To a large extent the floods and the sediment are now cut off by flood control and water storage dams.

#### Tectonic Setting

The trough is often interpreted as a fore-arc basin between the Sierra Nevada Mountains on the east and the accretionary wedge of the Coast Ranges on the west. Sediments eroded from the Sierra Nevada and the Coast Ranges were washed into the trough, at that time occupied by the sea. The shoreline ran along the eastern edge of the modern Great Valley where sediments were deposited in deltas at the mouths of Sierran rivers. These rivers carried the abundant outwash of the glacial erosion (as exemplified at Emerald Bay State Park) into the trough. The trough eventually filled with sediment and the seas retreated. (Photograph by Mike Fuller.)



The **Basin and Range** geomorphic province is characterized by subparallel, fault-bounded mountain ranges separated by down-dropped basins. Death Valley, the lowest area in the United States, is one of these down-dropped basins. Badwater, the lowest point in Death Valley, lies at 280 feet below sea level. In general, most of the valleys in the Basin and Range are actually elevated, with valley floors lying at more than 3,000 feet above sea level. The northernmost portion of the Basin and Range geomorphic province in California includes the Honey Lake Basin. The Basin and Range province is the westernmost part of the much larger Great Basin that extends across several states. The region is characterized by interior drainage with lakes and playas.

#### Tectonic Setting

The basin and range landscape forms in response to crustal thinning and extension (stretching and pulling apart from deep dynamic forces). California lies along the western edge of the province. For the last 40 million years, the Basin and Range has been stretching from east to west, resulting in tilt block mountains and intervening down-dropped basins. The State of Nevada is actually growing in area as a result of these extensional processes. (Photograph by Mike Fuller.)

The **Mojave Desert** is a broad interior region of isolated mountain ranges separated by expanses of desert plains. Sometimes referred to as the high desert, elevations in the Mojave Desert generally range between 3,000 to 6,000 feet. Because of the enclosed interior drainage, rainwater either seeps into the ground or is evaporated, resulting in many playas. Within the province, there are two important fault trends that control topography, a prominent northwest trend and a secondary east-west trend (an apparent alignment with the Transverse Ranges).

#### Tectonic Setting

The rocks in the Mojave Desert are progressively older from the west toward the east. Some of the oldest rocks (about 1.7 billion years old) in California are exposed in the eastern Mojave Desert. Here also are remnants of what was the western continental shelf during the formation of the Appalachian Mountains and the Pangaea supercontinent.

The Mojave Desert geomorphic province's wedge-shaped appearance is due to the Garlock Fault along its northern boundary (the southern boundary of the Sierra Nevada) and the San Andreas Fault along the southern boundary. Like the Basin and Range geomorphic province, this region has been growing from east to west. It is also being sliced north to south along a set of faults (the eastern California shear zone) that operate similar to and parallel with the San Andreas Fault. (Photograph by California State Parks)

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